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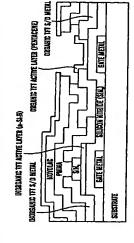
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(54) TILE: INTEGRATED INORGANIC/ORGANIC COMPLEMENTARY THIN-FILM TRANSISTOR CIRCUIT

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(57) Abstract

An integrated organic/incrganic complementary thin-film transistor circuit comprises a first and a second transistor which are operatively connected on a common authorizate, wherein the first transistor is an incrganic thin-film transistor and the second an organic during the increase of a common authorizate, wherein the first transistor is an o-channel transistor and the organic charles the increase of the transistors has a separate gate electrode and the organic early semiconductor material is in the case of a p-channel are transistors than the organizate electrodes are deposited from the organic charles in the appearance of electrodes are deposited from the same layer level in the thin-film students of relativistic is obtained than transistor are deposited on the same layer level in the thin-film students of the organic isolated from the organic extre semiconductor material in an organic p-channel transistor, and the organic extre semiconductor material in an organic p-channel transistor and confidence of the organic charles of the organic extre semiconductor material in an organic p-channel transistor and the organic extre semiconductor material in an organic p-channel transistor is in the organic active semiconductor material in an organic n-channel transistor of the organic charles of the organic charles of the organic charles organic than the organic charles of the organic charles or an expectively source and drain areas in the organic transistor and an rideot layer ordanel the inorganic p-the-film transistor is isolated electrically from the forgranic charles are considered to the organic charles are not the organic charles organic charles are not organic transistor in the organic charles in transistor is isolated electrically from

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Integrated inorganic/organic complementary thin-film transistor circuit.

thin-film transistor circuit, comprising a first and a second transistor which is operatively connected and provided on a common substrate, wherein the first transistor is an inorganic thin-film transistor and the second transistor an The invention concerns an integrated inorganic/organic complementary organic thin-film transistor. and wherein the complementary thin-film ransistor circuit forms a multilayer structure.

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first and a second transistor which are operatively connected and provided on thin-film structure with successively deposited and patterned thin-film layers. inorganic/organic complementary thin-film transistor circuit, comprising a The present invention also concerns methods for fabricating an integrated wherein the complementary thin-film transistor circuit forms a multilaver a common substrate. wherein the first transistor is an inorganic thin-film transistor and the second transistor an organic thin-film transistor, and

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electronic products, as they can provide very low static power dissipation for applications such as microprocessors. But complementary circuits may also be of interest for more general application. e.g. in portable battery-operated complementary integrated thin-film circuits with sufficient performance for semiconductors dominate the markets for a number of microelectronic Integrated circuits of silicon realized as complementary metal-oxide digital circuits. It has, however, turned out to be difficult to realize commercial applications. 15

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Hydrogenated thin-film transistors of silicon (a-Si:H TFT) have found a new with active matrix. However, complementary a-Si:H circuits are problematic, sabricated and with performance comparable to that which can be obtained application in thin-film components, particularly in liquid crystal displays transport mobility. Recently TFTs with organic active layers have been as the hole transport mobility typically is much lower than the electron with amorphous silicon devices (a-Si:H devices).

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For instance there is in US patent no. 5 347 144 (Garnier & al.) disclosed a thin-film field-effect transistor with an MIS structure which includes a thin semiconductor layer contacts a surface of a thin-film made of isolating semiconductor layer between the source and drain electrode. The thin material which at its second surface contacts a conducting grid. The

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semiconductor is made of at least one polyconjugated organic compound with hydrocarbons and among these polyacenes. The transistor of Garnier & al. is a determined molecular weight. As organic semiconductor material Garnier stated to be particularly suited as a switching or amplifying device. & al. among others mention different various aromatic polycyclic

properties. Further attempts have been made building complementary circuits with combinations of inorganic and organic devices on separate substrates Also simple organic complementary thin-film transistor circuits have been discussed in the literature, but have not shown the desired performance and with external connection.

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complementary circuit with an inorganic n-channel thin-film transistor and an In US patent no. 5 625 199 (Baumbach & al.) there is, however, disclosed a organic p-channel thin-film transistor. The n-channel thin-film transistor employs hydrogenated amorphous silicon as active material and the

ransistor circuit according to Baumbach & al. can be used for implementing p-channel of the organic thin-film transistor employs α -hexathienylene (a-6T) as active semiconductor material. The complementary thin-film an integrated complementary inverter or other complementary circuits.

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electrodes on both sides of the organic semiconductor layer, something which disadvantages both from a processual point of view as well as with regard to firstly is not necessary and additionally comports a number of disadvantages according to Baumbach & al. is, however, encumbered with a number of Saumbach & al. propose to provide respectively the source and drain The integrated complementary inorganic/organic thin-film transistor general application in more comprehensive transistor circuits. Thus 2 22

difficult to pattern contacts on the top of the organic semiconductor unless hin-film transistor must be formed in different steps and it will also be in the fabrication. Further the source and drain contacts of the organic shadow masks are used.

according to Baumbach & al, it is probable that an undesirable large leakage Nor has the complementary thin-film transistor according to Baumbach an isolated organic semiconductor material in the organic thin film transistor. As it will be desirable to be able to turn the inorganic transistor on and to urn the organic transistor off or vice versa using potential with the same sign, this may be problematic. In the complementary thin-film transistor 3 35

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of organic materials which may be used for forming active semiconductors of materials proposed. It is. however, evident from Baumbach & al. that the use will be problematic if the complementary thin-film transistor shall be used in Another disadvantage of the complementary thin-film transistor according to n-channel and the p-channel transistor. More complex transistor circuits built complex circuits. An inverter realized according to Baumbach & al. switches from complementary devices shall require that common electrodes are not used in these. Even in simple inverters a common gate electrode will give complementary thin-film transistor according to Baumbach & al. uses the as stated in the cited US patent at about 5V at a supply voltage of 7,2 V. inorganic transistor as n-channel transistor and the organic transistor as p-channel transistor, something which is understandable in light of the Baumbach & al. is that a common gate electrode is used both for the increased stray capacitance. Further it shall be remarked that the

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A first object of the present invention is hence to overcome the disadvantages and simultaneously have low static power consumption, such that they can be complementary inorganic/organic thin-film transistor circuit which is suited complementary thin-film transistor circuits which allow a cheap fabrication which are connected with prior art and particularly to provide an integrated for use in large transistor circuits. Another object is to provide used in portable battery-operated equipment.

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the n-type demands relatively complicated and costly fabricating processes

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and hence is not easy to realize for the time being.

inorganic/organic thin-film transistor circuits and this in as few process steps whereby it particularly shall be possible to realize the inorganic transistor as an n-channel transistor and the organic transistor as a p-channel transistor or A further object of the present invention is to provide an uncomplicated and as possible, while a device with good electric properties is obtained and inexpensive method for fabricating integrated complementary vice versa. 25 33

inorganic/organic complementary thin-film transistor circuit which according to the invention is characterized in that the organic thin-film transistor is an n-channel transistor and that the organic thin-film transistor is a p-channel transistor, or vice versa, the organic active transistor material in each case The above-mentioned and other objects are achieved with an integrated

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provided for each of the transistors, that the organic active semiconductor in an organic p-channel transistor in each case is provided electrically isolated n-channel organic semiconductor material, that separate gate electrodes are semiconductor in an organic n-channel transistor optionally is provided being respectively a p-channel organic semiconductor material or an from the inorganic n-channel transistor, and that the organic active electrically isolated from the inorganic p-channel transistor.

cadmium selenide (CdSe), cadmium telluride (CdTe), or composite inorganic single crystal silicon. copper-doped polycrystalline germanium (pc-Ge:Cu), According to the invention the inorganic active semiconductor material is advantageously selected among hydrogenated amorphous silicon (a-Si:H), hydrogenated or unhydrogenated microcrystalline silicon (µc-Si:H;µc-Si), nydrogenated or unhydrogenated polycrystalline silicon (pc-Si:H;pc-Si), emiconductors based on said materials, possibly in single crystal form. 2

naterial, particularly p-channel hydrogenated amorphous silicon (a-Si:H) inorganic active semiconductor material is preferably a p-channel silicon (a-Si:H), and where the inorganic transistor is a p-channel transistor, the inorganic active semiconductor material is preferably amorphous silicon Where the inorganic thin-film transistor is an n-channel transistor, the 2

polyconjugated organic compound or compounds are selected selected among compound with a specific molecular weight. It is then advantageous that the norganic thin-film transistor comprises at least one polyconjugated organic in an advantageous embodiment the active semiconductor material in the conjugated oligomers. polycyclic aromatic hydrocarbons, particularly 20

polyacenes. or polyenes. 22

advantageous that the organic active semiconductor material is pentacene, and where the organic thin-film transistor is an n-channel transistor, it is advantageous that the organic active semiconductor material is copper Where the organic thin-film transistor is a p-channel transistor, it is nexadecafluorophtalocyanide.

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source electrode and the drain electrode of the organic thin-film transistor is provided in one and the same level in the thin-film structure of the organic Finally, it is according to the invention particularly advantageous that the hin-film transistor.

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A first method for fabricating an integrated inorganic/organic complementary organic thin-film transistor on the same level in the thin-film structure of the isolated from the inorganic n-channel transistor and optionally providing the p-channel organic active semiconductor material or correspondingly forming n-channel organic active semiconductor material and a p-channel inorganic forming the inorganic thin-film transistor as an n-channel transistor and the the organic thin-film transistor as an n-channel transistor and the inorganic thin-film transistor as a p-channel transistor by depositing respectively an depositing material for the source electrode and the drain electrode of the organic thin-film transistor and in each case providing the organic active organic active semiconductive material in an organic n-channel transistor respectively an n-channel inorganic active semiconductor material and a thin film transistor circuit is according to the invention characterized by active semiconductor material, depositing separate gate electrodes for respectively the first and the second transistor on a common substrate, semiconductor material in an organic p-channel transistor electrically organic thin-film transistor as a p-channel transistor by depositing electrically isolated from the inorganic p-channel transistor.

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electrodes of the first transistor in form of a second metal over the source and nydrogenated polycrystalline silicon (n*pc-Si:H) as source and drain contacts the whole organic thin-film transistor and patterning this such that the source characterized by comprising steps for depositing separate gate electrodes of a ayer level in the thin-film structure, forming an isolating double layer over gate electrode, depositing an inorganic active semiconductor in the form of electrodes for the second transistor in the form of a third metal in the same hydrogenated amorphous silicon (a-Si:H) above one of the gate electrodes and drain electrodes and the gate isolator in the second transistor become depositing separate inorganic isolators of silicon nitride (SiN_x) over each which thus forms the gate electrode of the first transistor, depositing and exposed, whereafter a layer of pentacene is deposited above the isolating complementary thin-film transistor circuit is according to the invention patterning an n⁺ doped layer of either hydrogenated amorphous silicon drain contacts thereof, depositing and patterning the source and drain for the first transistor, depositing and patterning the source and drain (n^a-Si:H) or hydrogenated microcrystalline silicon (n^ μ c-Si:H) or first metal for each of the two transistors on a common substrate, A second method for fabricating an integrated inorganic/organic 25 30 35 2

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double layer and the exposed portion of the second transistor, the pentacene layer in the exposed portion forming the active semiconductor material of the organic thin-film transistor and being provided electrically isolated against the additional pentacene layer broken by a re-entrant edge of the profile of the isolating double layer.

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In an advantageous embodiment of the last-mentioned method according to the invention the steps for forming the inorganic thin-film transistor are realized in a tri-layer process which forms an inverted staggered three-layer

10 In another advantageous embodiment of the last-mentioned method according to the invention the steps for forming the inorganic thin-film transistor are realized in a back-channel etch process.

In an advantageous embodiment of the last-mentioned method according to the invention the active semiconductor in the form of pentacene in the organic thin-film transistor is isolated by a re-entrant profile of a broken double layer of polymethylmetacrylate (PMMA) and Novolac photoresist.

In an advantageous embodiment of the last-mentioned method according to the invention gold is evaporated thermally for forming the source and drain electrodes of the organic thin-film transistor.

20 Finally, the pentacene layer which is deposited over the isolating double layer can optionally be removed. The invention shall now be explained in more detail in connection with exemplary embodiments and with reference to the accompanying drawings wherein

fig. 1 shows a complementary thin-film transistor circuit according to prior art as exemplified by the above-mentioned US patent No. 5 675 199, fig. 2a a first embodiment of the complementary thin-film transistor circuit according to the invention,

fig. 2b a second embodiment of a complementary thin-film transistor circuit according to the invention,

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fig. 2c a variant of the embodiment in fig. 2b,

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fig. 3a a third embodiment of the complementary thin-film transistor circuit according to the invention.

fig. 3b a fourth embodiment of the complementary thin-film transistor circuit according to the invention.

fig. 3c a fifth embodiment of the complementary thin-film transistor circuit according to the invention.

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fig. 3d a variant of the embodiment in fig. fig. 3c,

figs. 4a-4r schematically the process steps in an embodiment of a method according to the present invention,

10 figs. 5a-5d a tri-layer etch process as used with a method according to the present invention. figs. 6a-6c a back-channel etch process as used with a method according to the present invention.

the present invention.

fig. 7a schematically a section through an inverter realized with the

complementary thin-film transistor circuit according to the present invention,

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fig. 7b the circuit diagram of the inverter in fig. 7a.

fig. 7c a line drawing based on a microphotograph of the actual inverter in fig. 7a realized in thin film technology.

fig. 8a the voltage transfer curve for an inverter realized as in fig. 7a,

20 fig. 8b a diagram of the transient current for an inverter realized as in fig. 7a,

fig. 9a a line drawing based on a microphotograph of an actual NAND gate realized with complementary thin-film transistor circuits according to the present invention,

fig. 9b a circuit diagram of the NAND gate in fig. 9a,

25 fig. 9c the output voltage of the NAND gate in fig. 9a.

fig. 10 a line drawing based on a microphotograph of an actual five-stage ring oscillator realized with complementary thin-film transistor circuits according to the present invention,

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fig. 11 the circuit diagram of the ring oscillator in fig. 10,

figs. 12a-12c respectively the gate delay, the power dissipation and the power dissipation product for the ring oscillator in fig. 10 as function of the supply voltage, and

figs. 13a-c respectively the gate delay, the power dissipation and the power dissipation product as function of the supply voltage for an eleven-stage ring oscillator realized with complementary thin-film transistor circuits according to the present invention.

First there shall now be given a discussion of prior art with the

- above-mentioned US patent No. 5 625 199 (Baumbach & al.) as starting point. Therein is disclosed a complementary circuit with inorganic n-channel thin-film transistor and an organic p-channel thin-film transistor, such as rendered in fig. 1. For both transistors a common gate electrode 2 of metal is provided on a substrate 1. Over the gate electrode is provided a dielectric 3 which forms the gate isolator and which typically is made of a
- which forms the gate isolator and which typically is made of a non-conducting polymer. Over the gate isolator 3 then follows a layer 4 of undoped amorphous silicon which forms the active layer of the inorganic n-channel transistor. On the a-Si layer 4 is provided a patterned isolation layer 5 which serves to prevent short circuit between the source and drain
- areas of the n-channel transistor. Over the layers 3, 4 and 5 a further layer 6 of n² amorphous silicon has been deposited and provides electrical contact to the active amorphous silicon layer 4. The source/drain electrodes 7 are deposited patterned such that the source electrode and drain electrode of the n-channel transistor are not short-circuited. The metal layer 7 is besides
 - patterned such that the n-channel and the p-channel transistors in the circuit are connected. Consequently the layer 7 extends towards the p-channel transistor and forms the source contact therein. Now follows a layer 8 of an isolating material, for instance silicon nitride, polyimide or another dielectric in order to isolate the source/drain electrodes 7 against the active organic
 - semiconductor layer 9 which is formed of α-hexathienylene (α-6T) and which for instance may be deposited by vacuum sublimation. Finally, the prior art circuit comprises the drain electrode 10 of the p-channel transistor. The contact metal may be made of an evaporated or sputtered layer of Au or Ag and will be connected to the positive supply voltage. This prior art complementary transistor circuit is then in a final step coated with a

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passivation layer 11. e.g. of silicon nitride or polyimide, to protect the

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deposited on a substrate and covered by a layer of silicon nitride which forms extends beyond this where it forms n' doped areas for source and drain in the the gate isolator. The inorganic active semiconductor material is here shown material of the source electrode of the inorganic transistor may be of another electrode is itself then deposited over the active semiconductor material and deposited over the gate isolator such that the source and drain electrodes of in the form of hydrogenated amorphous silicon (a-Si:H) and provided such A section through a first embodiment of a complementary transistor circuit that it registers with the gate electrode of the inorganic transistor, but also norganic transistor. The contact material proper for the drain or source hin-film structure. Over both the inorganic and the organic transistors' material for the source and drain electrodes of the organic transistor is metal than the metal in the gate electrode. Correspondingly the contact the organic transistor in each case are located on the same level in the electrodes for respectively the inorganic and the organic transistor are mutually isolated by a patterned isolation layer of silicon nitride. The according to the present invention is shown in fig. 2a. Separate gate source and drain contacts a double layer of respectively

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electrode of organic transistor. The broken re-entrant profile and the isolating provided in the form of a layer over the isolating double layer where this has semiconductor material contacts both the source and the drain electrodes of semiconductor material optionally may be removed where it covers the a re-entrant profile. The organic active semiconductor material is now the organic transistor and simultaneously also registers with the gate double layer provide a secure electrical isolation between the organic transistor and the inorganic transistor. Of course, the active organic not been removed and in the exposed portion thereof, such that the isolating double layer. In fig. 2a it is, however, retained. 25 3

transistor is exposed, the isolating double layer in this area in section having

such that the portion between the source and drain electrodes in the organic

polymethylmetacrylate and Novolac photoresist is provided, but patterned

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It is to be understood that the active inorganic semiconductor material is not restricted to a hydrogenated amorphous silicon, but may well consist of 35

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hydrogenated microcrystalline or polycrystalline silicon. The source and 2

- polyconjugated organic compounds with suitable properties and be formed by several such. As example of such polyconjugated organic compounds and as which includes or consists of phenylene groups which may be substituted, Correspondingly the organic active semiconductor material in the organic known in the art, it may be mentioned conjugated oligomers, the units of drain material may also be deposited separately and be different from the transistor is not restricted to pentacene, but may generally be made of channel area, e.g. n doped microcrystalline hydrogenated silicon. S
 - ortho-fused or ortho- and peri-fused aromatic polycyclic hydrocarbons with 4 and T2 independently represent -H or a lower alkyl and r is an integer which to 20 fused rings, polyenes with the formula H-C(T1)=C(T2)- H where T1 may vary from 8 to 50, as well as conjugated oligomers whose repeating organic semiconductor transistor contain at least 8 conjugated bonds and polyconjugated compound used as active semiconductor material in the units contain at least a five-link heterocycle. Generally shall a 2 2
- comprehensive discussion of these materials it shall besides be referred to the have a molecular weight which is not greater than about 2000. For a more ibove-mentioned US patent no. 5 347 144 (Garnier & al.).
- simplified version of the complementary thin-film transistor circuit. In fig. 2b material is removed outside the organic thin-film transistor. The mask layer semiconductor material in the p-channel transistor may be achieved with a of the photoresist may be retained as shown in fig. 2b. but it may also be As an alternative to the embodiment in Iig. 2a, the isolation of the active hin-film transistor circuit, whereafter the organic active semiconductor his is shown by providing a photoresist layer over the complementary. 20 22
- naterial by etching, as such materials usually are damaged or destroyed when hey are subjected to common photoresists and chemicals for treatment of the emoved such this is shown in fig. 2c. In each case the active semiconductor norganic transistor. In that connection it shall be remarked that generally it photoresist. However, it has turned out that a water-based etch process with material in the organic transistor becomes electrically isolated against the water-based material provides very good results. In the patterning of e.g. has been regarded as a problem to remove active organic semiconductor 8
- organic optoelectronic material may e.g polyvinyl alcohol as solvent and gelatine as photoresist be an advantageous alternative. Besides are both 35

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photolithography and printing other possible alternatives to etching – particularly printing may in the long run turn out to be both the simplest and cheapest.

Fig. 3a shows a section through an organic/inorganic thin-film transistor according to the present invention where an organic thin-film transistor with an n-channel organic semiconductor is employed. Fig. 3 shows the simplest embodiment possible, wherein separate gate electrodes are provided on the substrate, the gate isolator consists of the same material in both cases and the metal for the source/drain electrode similarly is the same for both transistors.

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As an example of an organic n-channel material may be mentioned copper hexadecafluorophtalocyanine (F₁₆CuPc) (see Y.Y. Lin & al., "Organic complementary ringoscillators", Appl. Phys. Lett., Vol. 74 No. 18 (1999)). This organic semiconductor shows field-effect mobilities up to 10⁻² cm/Vs and is not as sensitive to external conditions as other organic semiconductor materials of the n-type such as buckminsterfullerene (C₆₀).

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Organic n-channel thin-film transistors based on copper-hexadecalluorophtalocyanine (F₁₆CuPc) or another organic semiconductor material of the n-type may be combined with one of several inorganic p-channel semiconductor materials in order to form the complementary thin-film transistor circuit.

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As examples of suitable inorganic semiconductors of the p-type may be mentioned p-channel amorphous silicon which has field effect mobilities comparable with F₁₆CuPc. or copper-doped polycrystalline germanium (pc-Ge:Cu) which in the literature is shown used in combination with indium-doped cadmium selenide (Cd-Se:In) in a complementary polycrystalline thin-film technology (see J. Doutreloigne & al., "The electrical performance of a complementary CdSe:In/Ge:Cu thin film transistor technology for flat panel displays", Solid-State Electronics, Vol. 34 No. 2 (1991)). Polycrystalline germanium has displayed field-effect mobilities of about 5-15 cm²/Vs, but requires a more complicated processing

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Fig. 3b shows an embodiment of the complementary thin-film transistor circuit according to the invention with an n-channel transistor. The embodiment in fig. 3b is analog to that in fig. 2a, but with the same metal used for the source and drain electrodes in both transistors. The isolating double layer may be realized as in fig. 2a, namely consisting of polymethylmetacrylate and Novolac photoresist such that the portion above the n-channel organic semiconductor is exposed, the isolating double layer also here being broken by a re-entrant profile. The active semiconductor in the n-channel organic transistor will then be isolated from the p-channel

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inorganic transistor, something which may be advantageous, but which is not a necessary condition for using an organic active n-channel semiconductor material. The isolation of the organic active n-channel semiconductor material may also be achieved in corresponding manner as shown for the embodiment in fig. 2b, namely as shown in fig. 3c, where a photoresist is etched and masked such that the n-channel organic active semiconductor is isolated. The etch mask. i.e. the photoresist, may also here be removed from the organic n-channel transistor and it is then obtained the variant which is shown in fig. 3d of the embodiment in fig. 3c.

There shall now with reference to figs. 4a-4r which schematically show the process scheme for integrated complementary a-Si:H organic transistor technology be given a description of specific features in the fabrication of the complementary thin-film transistor circuit according to the invention. The inorganic a-Si:H thin-film transistor is made in a process which provides an inverted staggered three-layer structure, something which shall be described more closely in the following. The layers of a-Si:H/SiN were deposited using of plasma-enhanced chemical vapour deposition. The subsequent process step comprises standard lithographic methods and wet etching

techniques as well as sputtered deposition of source and drain metal for the inorganic thin-film transistor. The source and drain electrodes of the organic thin-film transistor were deposited by means of thermal evaporation. In order to isolate the active semiconductor material of the organic thin-film transistor, in this case pentacene, a re-entrant photoresist profile was used consisting of polymethylmetacrylate (PMMA) and Novolac photoresist which together forms an isolating double layer in the complementary transistor circuit. This is a necessary step, as thin-film transistors with pentacene as

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than amorphous silicon.

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leakage in the pentacene layer, but as pentacene is sensitive to most forms of With the method according to the invention the isolation is achieved during threshold, i.e. a positive voltage must be used on the gate electrode to turn photolitography after the deposition of the organic semiconductive layer. the deposition of the pentacene layer by breaking this over the re-entrant double-layer profile in the organic transistor. The maximum temperature semiconductor of pentacene in the organic transistor in order to prevent chemical processing, it is difficult to achieve isolation with the use of p-channel active semiconductor material usually will have a positive the transistor off. It is hence necessary to isolate an active p-channel which was used during the fabrication was 250°C.

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photoresist is now patterned with another mask II in order to actively define a uppermost silicon nitride layer is etched and in the subsequent process step in the lowermost nitride layer by means of a third mask III. The etching itself of shown in fig. 4b. By means of plasma-enhanced chemical vapour deposition, fig. 4f the layer of hydrogenated amorphous silicon is etched. In the process however, substantially will be self-explanatory to a person skilled in the art. In fig. 4a the gate electrode metal is deposited on the substrate by sputtering a tri-layer structure is thereafter deposited. consisting of a gate isolator $\mathsf{SiN}_{\mathsf{x}}$ step shown in fig. 4g a photoresist is patterned for etching of i-stopper and explicitly be discussed with a concrete short reference to figs. 4a-4r which, over both gate electrodes. thereabove a layer of hydrogenated amorphous silicon and finally an isolation layer, once again formed of silicon nitride, Now the process steps for the fabrication of a transistor of this kind shall and then the separate gate electrodes are patterned with a first mask I as hin-film transistor with hydrogenated amorphous silicon. In fig. 4e the the i-stopper and the lowermost silicon nitride layer is shown in fig. 4h. such as shown in fig. 4c. In the subsequent step shown in fig. 4d a

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fig. 41 the source/drain metal M2 for the organic transistor was lifted off and from the first metal used in the gate electrodes. In the process step shown in chemical vapour deposition and in the subsequent process step in fig. 4j this ift-off of source/drain electrode metal. This is sputtered in the process step as shown in fig. 4k and is denoted with M2 which may be a metal different shown in fig. 4i n a-Si:H is now deposited by means of plasma-enhanced In order to realize the source and drain areas of the n-channel transistor as takes place by means of a fourth mask IV for patterning a photoresist for 9 35

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hen follows in the process step shown in fig. 4m an etching of the n layer of hydrogenated amorphous silicon which hence shall provide the source and drain areas of the inorganic transistor. Now follows in the process step shown in fig. 4n a patterning of a photoresist ransistor appears with source and drain electrodes of the metal M3 provided for lift-off of the metallization of the organic thin-film transistor. This takes place by means of a fifth mask V. A metal layer of a third metal M3 is now thin-film transistor electrically against the inorganic thin-film transistor is now by means of photo-lithography deposited a double layer consisting of collows the lift-off of this metal layer M3, such that the organic thin-film in the same level in the thin-film structure. In order to isolate the organic polymethylmetacrylate PMIMA and for instance Novolac photoresist. The deposited over the whole transistor circuit, as shown in fig. 40, and then S 2

fig. 4q. Finally is now the organic active semiconductor material deposited in re-entrant broken profiles of the isolating double layer, such this is shown in portion the active p-channel semiconductor material of the organic transistor. solating double layer is patterned such that the source and drain electrodes he form of pentacene over the whole circuit and provides in the exposed of the metal M3 for the organic thin-film transistor are exposed between

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complementary organic thin-film transistor circuit according to the invention it shall be understood that the pentacene layer where it covers the isolating double layer besides may be removed therefrom in a concluding not shown process step. Further may, of course, electrically isolating passivation and planarization layers be deposited over the whole complementary thin-film circuit, such this is known in the art. but not here specifically shown. The now appears substantially as shown in fig. 4r and corresponding to the embodiment shown in fig. 2a.

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deposited on the patterned gate electrode. The uppermost silicon nitride layer the source and drain electrodes is patterned and the doped amorphous silicon The tri-layer etch process as used with the present invention and as rendered lydrogenated silicon is deposited all over as shown in fig. 5c. The metal of somewhat greater detail with reference to figs. 5a-5d. In the tri-layer etch hydrogenated amorphous silicon and a further layer of silicon nitride are in the process steps as shown in figs. 4c-h shall now be discussed in process as shown in fig. 5a, a triple layer of silicon nitride, undoped is patterned as shown in fig. 5b and an n+ doped layer of amorphous

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fig. 5d. As the uppermost silicon nitride layer protects the channel area in the the source and drain electrodes must be patterned on the top of the uppermost silicon nitride layer which is patterned with the channel length, this requires tri-layer process requires two deposition steps of amorphous silicon and as naterial over the uppermost silicon nitride layer etched away, as shown in inorganic thin-film transistor, this etch step is not critical. However, the a more aggressive photolithography for a given channel length.

S

in the channel area is a critical step. Typically back-channel etching results in hydrogenated amorphous silicon in the channel area is etched away, such this is shown in fig. 6b and fig. 6c respectively. The back-channel etch process is very simple, but the etching of the n doped hydrogenated amorphous silicon inorganic thin-film transistors with poorer quality than that may be obtained followed by undoped hydrogenated silicon and nt doped silicon as well as a further layer of n* doped hydrogenated amorphous silicon. This is shown in The back-channel etch process is shown in fig. 6a-6c. An isolation layer of silicon nitride is deposited over the gate electrode and the substrate, and fig. 6a. The source and drain electrodes are patterned and the doped by using a three-layer etch process.

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invention. Functionally the inverter in fig. 7a corresponds substantially to the electrode contact may then be deposited in the same process step as shown in ransistor as well as the inverter gate contact against the inorganic transistor. inverter is based on a p-channel semiconductor material, viz. pentacene, and semiconductor material in the inorganic transistor. As the input signal to the complementary transistor circuit according to prior art as rendered in fig. 1, out is based on the embodiment according to the present invention such this fig. 4a-4b with the use of mask I. As in fig. 2a the isolating double layer of polymethylmetacrylate on Novolac photoresist will isolate both the organic hydrogenated amorphous silicon in doped and undoped form is used as the inverter shall be conveyed to the gate electrodes, there is for this purpose for instance is shown in fig. 2a. As therein the organic transistor of the nverter, be removed. The well-known schematic circuit diagram of the Fig. 7a shows a schematic section through an inverter formed with the provided a gate electrode contact as shown to left in fig. 7a. This gate isolating double layer as well as over the gate electrode contact of the integrated complementary thin-film transistor circuit according to the Besides may also here the pentacene layer which is provided over the 2 8 25 33

shown by the line drawing in fig. 7c. The organic thin-film transistor is here complementary transistor circuit and a method according to the invention is ocated at left and the inorganic thin-film transistor in the complementary inverter shown in fig. 7b and an inverter realized with use of a

Fig. 8a shows the voltage transfer curves for different supply voltages for an inverter with a β ratio of 1. The β ratio is here defined by

thin-film transistor circuit at right in fig. 7c.

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$$\beta = \frac{(W/L)_{a-3cH}}{W/I}$$

In this regard it shall be remarked that in CMOS circuits both transistors may he voltage levels of the complementary thin-film transistor circuit according to the invention. The transition current for the inverter reaches a top near the supply voltage of 20 V. The on voltage of the inverter is equal to the supply logic transition voltage and is otherwise very low, such this is evident from voltage and the off voltage is 0 V. This shows the complete maintenance of - The inverter shows sharp transitions with a gain which exceeds 22 for a sometimes defined as the width/length relationship W/L for the n-channel levice divided by the length/width relationship for the p-channel device. be operated both as driver and load. Due to a topological similarity β is according to the present invention has a true complementary behaviour. ig. 8b. This shows that the complementary thin-film transistor circuit 2 15 2

gate is of course obtained, the output of which then becoming the inverted of gate realized by means of a complementary transistor circuit according to the corresponding schematic circuit diagram in fig. 9b. By connecting the output With the complementary thin-film transistor circuit according to the present known in the CMOS-technology. An example of a complementary NANDnvention it is, of course, possible to realize logic gates as otherwise wellof the NAND gate to the inverter shown in fig. 7c a complementary AND the output signal from the NAND gate. The voltage transfer curve for present invention is shown in the line drawing in fig. 9a and the 25

corresponding Boolean functions be realized with the use of a NAND gate as that generally may all logic gates as known in the CMOS technology and the hese are shown in fig. 8a. A person skilled in the art will. of course, realize different input voltages for the NAND gate is shown in fig. 9c and has the same properties as the voltage transfer curves for the simple inverter such ಜ

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shown in fig. 9a and inverters as shown in fig. 7c. The integrated complementary thin-film transistor circuit according to the invention is generally used for realizing logic gates in complementary thin-film

technology.

S by means of the integrated complementary thin-film circuits ring oscillators were made with respectively 5 and 11 inverter stages and with different β ratios. These ring oscillators show a single gate delay as low as 5 μs, a gate power dissipation less than 0.2 μW per stage and a power delay product as low as 15 pJ. The gate delay decreases fast with the increasing supply voltage, such that high operating frequencies may be obtained with the relatively low supply voltage.

A line drawing of a five-stage ring oscillator is shown in fig. 10 and with the circuit diagram rendered in fig. 11. In addition to the five inverter stages an additional sixth inverter is used for isolating the circuit from the capacity load of an oscilloscope used for measuring the characteristics of the ring oscillator. From the measured oscillation frequency the delay of a single inverter stage can be derived. Fig. 12a shows the single gate delay for the shown five-stage ring oscillator, fig. 12b power dissipation and fig. 12c the power delay product for the same, all figures showing these characteristics for a β ratio of 1/2.

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A ring oscillator with eleven inverter steps is realized in corresponding manner with the use of the integrated complementary thin-film circuit according to the present invention, but not shown herein. Fig. 13a, 13b and 13c, however, show the corresponding characteristics for this eleven-stage ring oscillator as shown in fig. 12a-12c, but with a β ratio of 1/3.

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The methods according to the present invention are simple and hence make it possible to fabricate integrated complementary thin-film transistor circuits according to the invention at low costs. Complementary transistor circuits have an inherent low static power consumption, something which is of importance for applications based on battery power. This makes the complementary thin-film transistor circuit according to the invention applicable in control circuits for liquid crystal displays in portable PCs, so-called "lap-tops" or for low-level implementation such as programmable tags. The circuits according to the invention have high switching amplification and very good maintenance of the logic level in addition to low

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static power consumption. The gate delay in the transistor circuits fabricated according to the invention measured by means of ring oscillators is as mentioned as low as 5μs, the fastest speed up to now obtained with circuits which use organic transistors.

- 5 The hybrid integrated complementary thin-film technology, wherein the organic thin-film transistor may be an n-channel transistor and the organic transistor a p-channel transistor or vice versa, is of course, not restricted to use of the active semiconductor materials as mentioned in the exemplary embodiments. The on-going development of suitable organic as well as inorganic semiconductor materials makes it probable that in the future both
- not gains scilicontactor matching many in a swell as p-channel active organic semiconductor materials and correspondingly n- as well as p-channel inorganic active semiconductor materials with further improved properties may be employed. Composite inorganic semiconductor compounds may be of interest and the same applies to single crystal silicon, while on the other hand gallium arsenide for the time being appears less probable. but shall in no way be excluded in future hybrid complementary thin-film transistor circuits of the kind disclosed herein.

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CLAIMS

connected and provided on a common substrate, wherein the first transistor is organic active transistor material in each case being respectively a p-channel An integrated inorganic/organic complementary thin-film transistor thin-film transistor, and wherein the complementary thin-film transistor organic semiconductor material or an n-channel organic semiconductor the inorganic thin-film transistor is an n-channel transistor and that the organic thin-film transistor is a p-channel transistor, or vice versa, the circuit comprising a first and a second transistor which are operatively an inorganic thin-film transistor and the second transistor an organic circuit forms a multilayer thin-film structure, characterized in that

that the organic active semiconductor in an organic p-channel transistor in optionally is provided electrically isolated from the inorganic p-channel that the organic active semiconductor in an organic n-channel transistor each case is provided electrically isolated from the inorganic n-channel that separate gate electrodes are provided for each of the transistors, transistor, and

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- unhydrogenated polycrystalline silicon (pc-Si:H;pc-Si), single crystal silicon, characterized in that the inorganic active semiconductor material is selected (CdSe), cadmium telluride (CdTe), or composite inorganic semiconductors unhydrogenated microcrystalline silicon (µc-Si:H;µc-Si), hydrogenated or A complementary thin-film transistor circuit according to claim 1, copper-doped polycrystalline germanium (pc-Ge:Cu), cadmium selenide among hydrogenated amorphous silicon (a-Si:H), hydrogenated or based on said materials, possibly in single crystal form. 2 22
- 3. A complementary thin-film transistor circuit according to claim 2 characterized in that the inorganic active semiconductor material is wherein the inorganic transistor is an n-channel transistor, hydrogenated amorphous silicon (a-Si:H). 3
- A complementary thin-film transistor circuit according to claim 2, characterized in that the inorganic active semiconductor material is a wherein the inorganic transistor is a p-channel transistor,

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p-channel silicon material, particularly p-channel hydrogenated amorphous silicon (a-Si:H).

- A complementary thin-film transistor circuit according to claim 1, characterized in that the active semiconductor material in the organic
- thin-film transistor comprises at least one polyconjugated organic compound with a specific molecular weight. 'n
- characterized in that the polyconjugated organic compound or compounds are A complementary thin-film transistor circuit according to claim 5, selected among conjugated oligomers, polycyclic aromatic hydrocarbons,
 - particularly polyacenes, or polyenes. 2
- A complementary thin-film transistor circuit according to claim 6, characterized in that the organic semiconductor material is pentacene. wherein the organic thin-film transistor is a p-channel transistor,
- A complementary thin-film transistor circuit according to claim 1, characterized in that the organic active semiconductor material is copper wherein the organic thin-film transistor is an n-channel transistor, hexadecafluorophtalocyanide (F16CuPc). 15
- A complementary thin-film transistor circuit according to claim 1, organic thin-film transistor are provided in one and the same level in the characterized in that the source electrode and the drain electrode of the thin-film structure of the organic thin-film transistor. 20
- substrate, wherein the first transistor is an inorganic thin-film transistor and complementary thin-film transistor circuit comprising a first and a second complementary thin-film transistor circuit forms a multilayer thin-film transistor which are operatively connected and provided on a common structure with successively deposited and patterned thin-film layers, the second transistor a organic thin-film transistor, and wherein the A method for fabricating an integrated inorganic/organic 25
- depositing respectively an n-channel inorganic active semiconductor material characterized by forming the inorganic thin-film transistor as an n-channel and a p-channel organic active semiconductor material or correspondingly forming the organic thin-film transistor as an n-channel transistor and the transistor and the organic thin-film transistor as a p-channel transistor by norganic thin-film transistor as a p-channel transistor by depositing 3

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respectively an n-channel organic active semiconductor material and a p-channel inorganic active semiconductor material, depositing separate gate electrodes for respectively the first and the second transistor on a common substrate, depositing material for the source electrode and the drain electrode of the organic thin-film transistor on the same level in the thin-film structure of the organic thin-film transistor and in each case providing the organic active semiconductor material in an organic p-channel transistor electrically isolated from the inorganic n-channel transistor and optionally providing the organic active semiconductive material in an organic n-channel transistor electrically isolated from the inorganic p-channel transistor.

11. A method for fabricating an inorganic/organic complementary thin-film transistor circuit comprising a first and a second transistor which are operatively connected and provided on a common substrate, wherein the first transistor is an inorganic thin-film transistor and the second transistor an organic thin-film transistor, wherein the complementary thin-film transistor circuit forms a multilayer thin-film structure with successively deposited and patterned thin-film layers, and wherein the method is characterized by comprising steps for depositing separate gate electrodes of a first metal for

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- each of the two transistors on a common substrate,
 depositing separate inorganic isolators of silicon nitride (SiNx) over each
 gate electrode,
- depositing an inorganic active semiconductor in the form of hydrogenated amorphous silicon (a-Si:H) above one of the gate electrodes which thus forms the gate electrode of the first transistor, depositing and patterning an π^{*} doped layer of either hydrogenated amorphous silicon (π^a-Si:H) or hydrogenated microcrystalline silicon (π^μμc-Si:H) or hydrogenated polycrystalline silicon (π^{*}pc-Si:H) as source and drain contacts for the first

transistor, depositing and patterning the source and drain electrodes of the

first transistor in form of a second metal over the source and drain contacts thereof, depositing and patterning the source and drain electrodes for the second transistor in the form of a third metal in the same layer level in the thin-film structure, forming an isolating double layer over the whole organic thin-film transistor and patterning this such that the source and drain electrodes and the gate isolator in the second transistor become exposed, whereafter a layer of pentacene is deposited above the isolating double layer and the exposed portion of the second transistor, the pentacene layer in the exposed portion forming the active semiconductor material of the organic

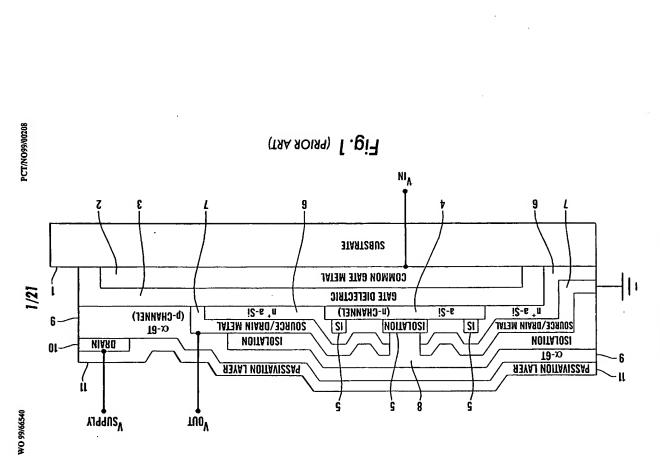
- thin-film transistor and being provided electrically isolated against the additional pentacene layer broken by a re-entrant edge of the profile of the isolating double layer.
- 12. A method according to claim 11, characterized by realizing the steps for forming the inorganic thin-film transistor in a tri-layer process which forms an inverted staggered tri-layer structure.
- 13. A method according to claim 11, characterized by realizing the steps forming the inorganic thin-film transistor in a back-channel etch process.
- 14. A method according to claim 11, characterized by isolating the active semiconductor in the form of pentacene in the organic thin-film transistor by a re-entrant profile of a broken double layer of polymethylmetacrylate (PMMA) and Novolac photoresist.
- A method according to claim 11, characterized by evaporating gold thermally for forming the source and drain electrodes of the organic thin-film transistor.

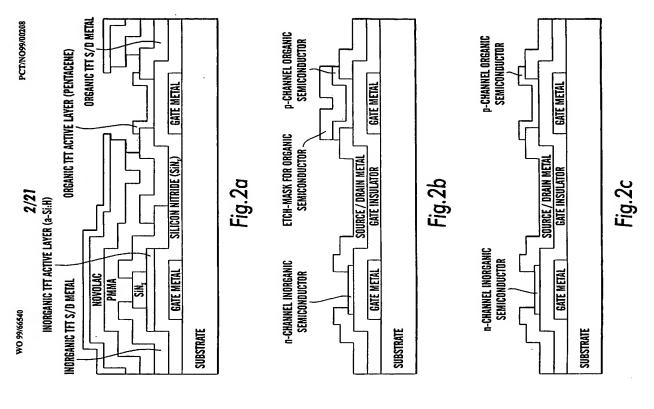
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16. A method according to claim 11. characterized by optionally removing the pentacene layer which has been deposited over the isolating double layer.

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p-CHANNEL INORGANIC Semiconductor

ETCH-MASK FOR ORGANIC SEMICONDUCTOR

n-CHANNEL ORGANIC SEMICONDUCTOR GATE METAL

SOURCE / ORAIN METAL

GATE INSULATOR

GATE METAL

SUBSTRATE

Fig.3c

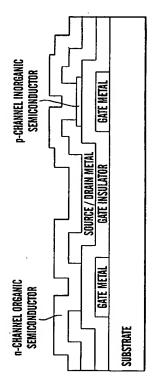


Fig.3a

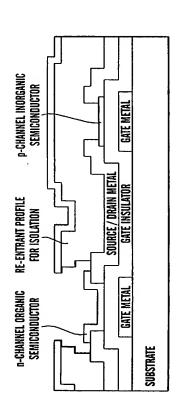
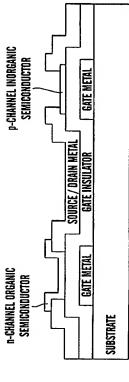


Fig.3b





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SPUTTER OF GATE METAL.

GATE METAL SUBSTRATE Fig.4a

DEFINITION OF GATE METAL PATTERN (MASK I).

GATE METAL GATE METAL SUBSTRATE

Fig.4b

PECVO OF TRI-LAYER:

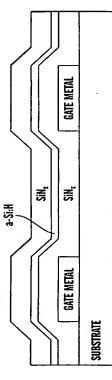


Fig.4c

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PATTERING OF PHOTORESIST FOR ACTIVE DEFINITION OF A-SI:H IFTS (MASK II).

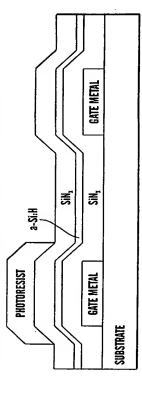


Fig.4d

ETCHING OF TOP NITRIDE LAYER:

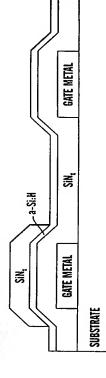


Fig.4e

ETCHING OF a-Si:H LAYER:

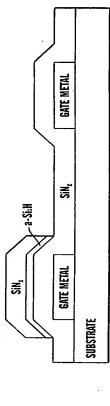


Fig.4f

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PATTERNING OF PR FOR ETCH OF 1-STOPPER AND BOTTOM NITRIDE LAYER (MASK 111);

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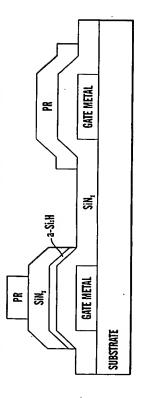


Fig.4g

ETCHING OF 1-STOPPER AND BOTTOM NITRIDE LAYER.

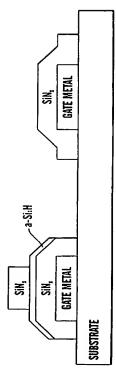


Fig.4h

PECVO OF n⁺ a-Si:H:

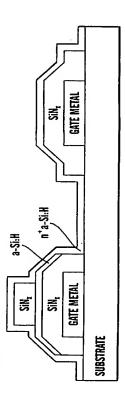


Fig.4i

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PATTERNING OF PR FOR LIFTOFF (MASK IV).

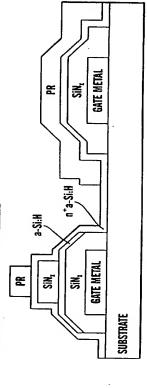


Fig.4j

SPUTTERING OF SOURCE / DRAIN METAL OF a-Si.H TFTs.

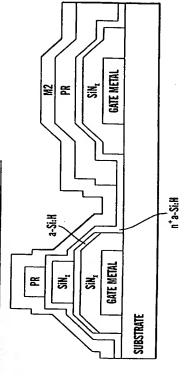
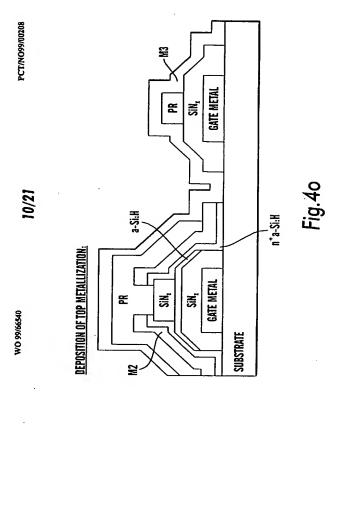


Fig.4k

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GATE METAL

GATE METAL

SUBSTRATE

SIN,

n^a-Si:H

a-Si:H

SiN,

Z Z Fig.41

ETCHING OF n*LAYER:

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LIFTOFF OF a-Si:H SOURCE / DRAIN METAL:

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PATTERING OF PHOTORESIST FOR LIFTOFF OF ORGANIC TFT METALLIZATION (MASK V).

M2

A2Sin,

Sin,

Sin,

Sin,

Substrate

GATE METAL

GATE METAL

SUBSTRATE

Si.

n*a-Si:H

Sil,

a-Si:H

LIFTOFF OF TOP METALLIZATION:

GATE METAL

GATE METAL

SUBSTRATE

SiN

S.

Fig.4m

SS.

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Fig.4n

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Fig.4p

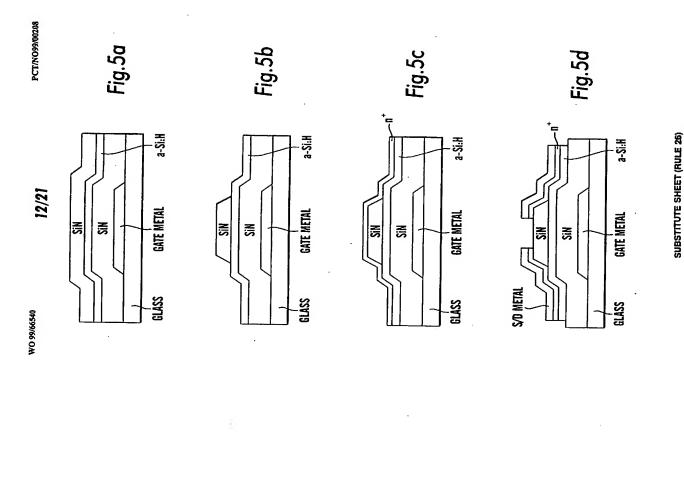


Fig.4q

n⁺a-Si:H

PENTACENE

a-Si:H

DEPOSITION OF PENTACENE ORGANIC SEMICONDUCTOR:

SIN, GATE METAL

GATE METAL

SUBSTRATE

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DOUBLE LAYER LITHOGRAPHY FOR ISOLATION:

SIN, GATE METAL

GATE METAL

SUBSTRATE

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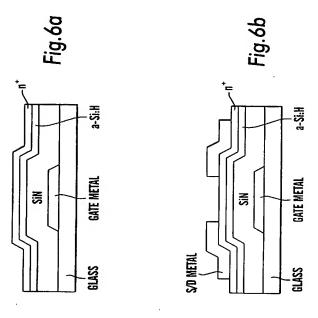
PA AM

a-Si:H

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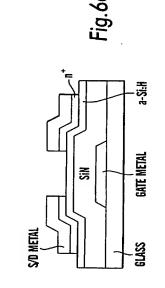
Fig.4r

n*a-Si:H



SINX

PENTACENE TFT S/D METAL



SUBSTRATE GATE CONT.

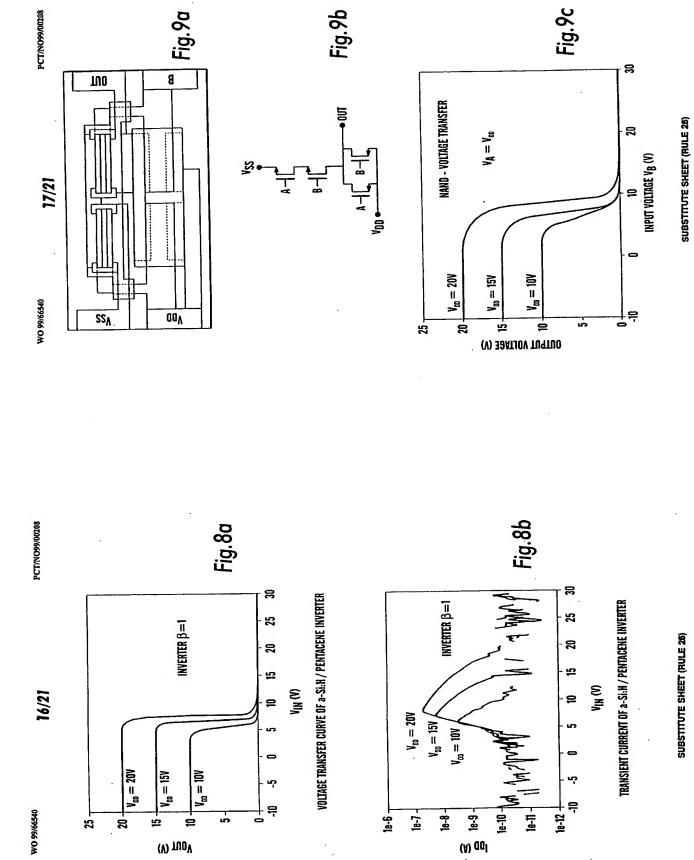
a-Si:H TFT S/D METAL

Fig.∑a H:i2-6⁺n H:iZ-6

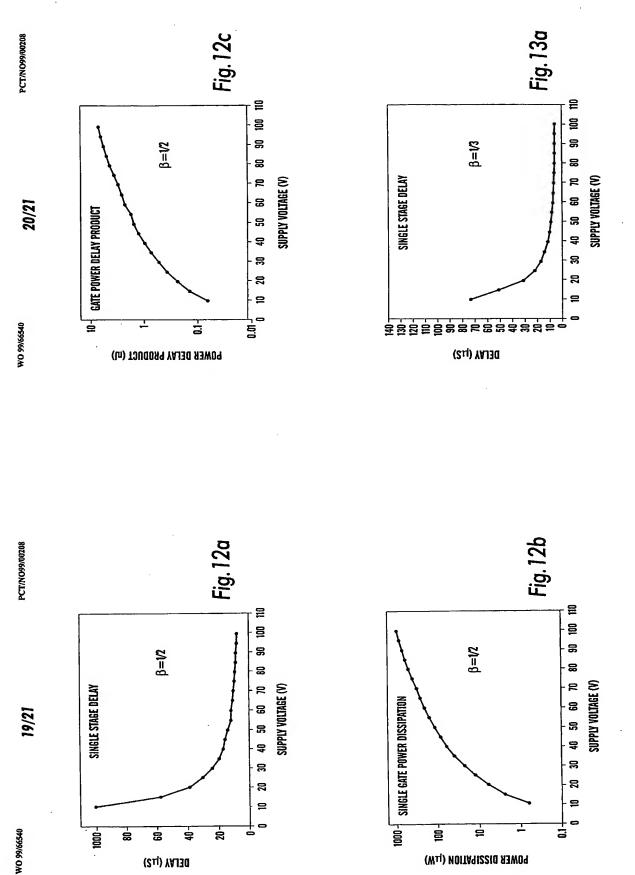
SINX

XNiS

AMM9



(V) TUOV

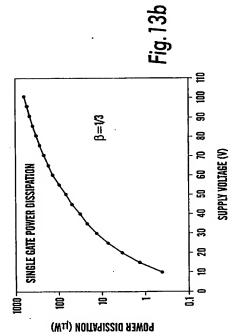


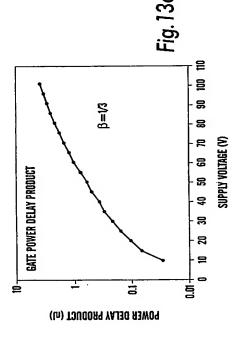
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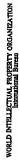
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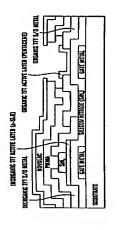




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(72) Inventore; and (72) Inventore; and (73) Inventore; and (73) Inventore/Applicates (for US oat); JACKSON, Thoras [USVOS]; 1348 Dearfield Drive, State College, P.A. 16801 [USVOS]; 1348 Dearfield Drive, State College, P.A. 16801 [USV, TANA, ASSON, Deniel, B. [USVOS]; 240 Les Almons Road, Surta Rosa, C.A. 95409 (US). HAOEN, Klant (DEUG); Apartment B. 1670 West College, Avenue, State College, PA 16801 (US), GUNDLACH, David, J. (USVOS); Apartment F. 445 [Watpoclant] Drive, State College, PA 16801 (US).	Decrease Published Publi
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4 A	

(54) THE: AN INTEGRATED INORGANICORGANIC COMPLEMENTARY THIN-FILM TRANSISTOR CIRCUIT AND A METHOD FOR ITS PRODUCTION



(57) Abstract

An integrated organic/inorganic complementary thin-film trunsistors circuit comprises a first and a second trunsistor which are operatively connected on a common substrate, wherein the film trunsistor is in the inorganic thin-film trunsistor and the second an organic thin-film trunsistor is a p-channel trunsistor in the organic station of the trunsistor is a p-channel trunsistor and the organic thin-film trunsistor is a p-channel trunsistor and the organic thin-film trunsistor is a p-channel trunsistor as semiconductor in the togenic thin-film trunsistor is a p-channel as transistor circuit of this kind separate gate electrode and the organic active semiconductor material is in the case of a p-channel a transistor circuit of this kind separate gate electrodes are deposited for each trunsistor on a common substrate, the material for the source film transistor are deposited for each trunsistor on a common substrate, the material for the source film transistors are deposited for the organic level in the thin-film structure of the organic thin-film transistor, and the organic en-channel transistor, and the organic extranel trunsistor is provided electrically isolated form the inorganic p-channel transistor.

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1 INTERNATIONAL SEARCH REPORT

International application No. PCT/NO 99/00208

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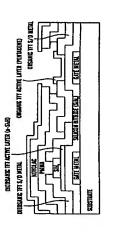


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(72) Inventors; and (70 or.); IACKSON, Thomas Published (75) Inventorspapileants (70 or.) or.); IACKSON, Thomas IGNUS; 1348 Deerfield Drive, State College, PA 16801 (103). BOMER, Mathias IDBUS; Apartment 125, 201 Vator Boulewart, State Oldege, PA 16803 (103). THOMASSON, Daniel, B. (10315); 240 Los Alamos Road, State Road, CA 95499 (103). HAGEN, Klant (DEUUS); Apartment B. 1670 West College, PA 16801 (103). GINDIA-CH, David, J. (1195/US); Apartment Fl. 445 (Warpolani Drive, State College, PA 16801 (185).	N, Thoma Y, 201 Vain OMASSON Sente Ross Apartmen Apartmen PA 1680	Published With international search report. Before the expiration of the time limit for amending the claims and to be republished in the even of the receipt of amendment. In English translation (filted in Norwegian). (88) Date of publication of the international search report:

(\$4) TIME: AN INTEGRATED INORGANICORGANIC COMPLEMENTARY THIN-FILM TRANSISTOR CIRCUIT AND A METHOD FOR ITS PRODUCTION

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(57) Abstract

An integrated organic/inorganic complementary thin-film transistor circuit comprises a first and a second transistor which are operatively connected on a common substante, wherein the first transistor is an inchange of thin-film transistor and the second an organic thin-film transistor. The inorganic thin-film transistor is an inchannel transistor and the organic thin-film transistor is a parameter, and inchannel transistor and the organic thin-film transistor is a parameter of the transistor of the transistor has a separate game felenched and the organic active semiconductor material is in the case of a p-channel at transistor increases the infinite transistor described by the transistor of the organic thin-film transistor are deposited for each transistor on a common substante, the material for the source and the drain electrodes are the organic exitor are deposited on the same hyer level in the thin-film structure of the organic thin-film transistor are deposited on the same byte level in the thin-film structure of the organic thin-film transistor, and the organic carrier than organic n-channel transistor, and the organic active semiconductor material in an organic n-channel transistor optionally stolated from the inorganic p-channel transistor.

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AN INTEGRATED INORGANIC/ORGANIC COMPLEMENTARY THIN-FILM TRANSISTOR CIRCUIT AND A METHOD FOR ITS PRODUCTION

The invention concerns an integrated inorganic/organic complementary thin-film transistor circuit, comprising a first and a second transistor which is operatively connected and provided on a common substrate, wherein the first transistor is an inorganic thin-film transistor and the second transistor an organic thin-film transistor, and wherein the complementary thin-film transistor circuit forms a multilayer structure.

The present invention also concerns methods for fabricating an integrated inorganic/organic complementary thin-film transistor circuit, comprising a first and a second transistor which are operatively connected and provided on a common substrate, wherein the first transistor is an inorganic thin-film transistor and the second transistor an organic thin-film transistor, and wherein the complementary thin-film transistor circuit forms a multilayer thin-film structure with successively deposited and patterned thin-film layers.

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Integrated circuits of silicon realized as complementary metal-oxide semiconductors dominate the markets for a number of microelectronic applications such as microprocessors. But complementary circuits may also be of interest for more general application, e.g. in portable battery-operated electronic products, as they can provide very low static power dissipation for digital circuits. It has, however, turned out to be difficult to realize complementary integrated thin-film circuits with sufficient performance for commercial applications.

Hydrogenated thin-film transistors of silicon (a-Si:H TFT) have found a new application in thin-film components, particularly in liquid crystal displays with active matrix. However, complementary a-Si:H circuits are problematic, as the hole transport mobility typically is much lower than the electron transport mobility. Recently TFTs with organic active layers have been fabricated and with performance comparable to that which can be obtained with amorphous silicon devices (a-Si:H devices).

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For instance there is in US patent no. 5 347 144 (Garnier & al.) disclosed a thin-film field-effect transistor with an MIS structure which includes a thin semiconductor layer between the source and drain electrode. The thin semiconductor layer contacts a surface of a thin-film made of isolating material which at its second surface contacts a conducting grid. The

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semiconductor is made of at least one polyconjugated organic compound with a determined molecular weight. As organic semiconductor material Garnier & al. among others mention different various aromatic polycyclic hydrocarbons and among these polyacenes. The transistor of Garnier & al. is stated to be particularly suited as a switching or amplifying device.

Also simple organic complementary thin-film transistor circuits have been discussed in the literature, but have not shown the desired performance properties. Further attempts have been made building complementary circuits with combinations of inorganic and organic devices on separate substrates and with external connection.

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In US patent no. 5 625 199 (Baumbach & al.) there is, however, disclosed a complementary circuit with an inorganic n-channel thin-film transistor and an organic p-channel thin-film transistor employs hydrogenated amorphous silicon as active material and the p-channel of the organic thin-film transistor employs α-hexathienylene (α-6T) as active semiconductor material. The complementary thin-film transistor circuit according to Baumbach & al. can be used for implementing an integrated complementary inverter or other complementary circuits.

The integrated complementary inorganic/organic thin-film transistor according to Baumbach & al. is, however, encumbered with a number of disadvantages both from a processual point of view as well as with regard to general application in more comprehensive transistor circuits. Thus Baumbach & al. propose to provide respectively the source and drain electrodes on both sides of the organic semiconductor layer, something which firstly is not necessary and additionally comports a number of disadvantages in the fabrication. Further the source and drain contacts of the organic thin-film transistor must be formed in different steps and it will also be difficult to pattern contacts on the top of the organic semiconductor unless shadow masks are used.

30 Nor has the complementary thin-film transistor according to Baumbach an isolated organic semiconductor material in the organic thin film transistor.

As it will be desirable to be able to turn the inorganic transistor on and to turn the organic transistor off or vice versa using potential with the same sign, this may be problematic. In the complementary thin-film transistor according to Baumbach & al. it is probable that an undesirable large leakage

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will be problematic if the complementary thin-film transistor shall be used in complex circuits. An inverter realized according to Baumbach & al. switches as stated in the cited US patent at about 5V at a supply voltage of 7,2 V. Another disadvantage of the complementary thin-film transistor according to Baumbach & al. is that a common gate electrode is used both for the n-channel and the p-channel transistor. More complex transistor circuits built from complementary devices shall require that common electrodes are not used in these. Even in simple inverters a common gate electrode will give increased stray capacitance. Further it shall be remarked that the

complementary thin-film transistor according to Baumbach & al. uses the inorganic transistor as n-channel transistor and the organic transistor as inorganic transistor as n-channel transistor and the organic transistor as p-channel transistor. something which is understandable in light of the materials proposed. It is, however, evident from Baumbach & al. that the use of organic materials which may be used for forming active semiconductors of the n-type demands relatively complicated and costly fabricating processes and hence is not easy to realize for the time being.

A first object of the present invention is hence to overcome the disadvantages which are connected with prior art and particularly to provide an integrated complementary inorganic vorganic thin-film transistor circuit which is suited for use in large transistor circuits. Another object is to provide complementary thin-film transistor circuits which allow a cheap fabrication and simultaneously have low static power consumption, such that they can be used in portable battery-operated equipment.

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A further object of the present invention is to provide an uncomplicated and inexpensive method for fabricating integrated complementary inorganic/organic thin-film transistor circuits and this in as few process steps as possible, while a device with good electric properties is obtained and whereby it particularly shall be possible to realize the inorganic transistor as an n-channel transistor and the organic transistor or

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The above-mentioned and other objects are achieved with an integrated inorganic/organic complementary thin-film transistor circuit which according to the invention is characterized in that the organic thin-film transistor is an n-channel transistor and that the organic thin-film transistor is a p-channel transistor, or vice versa, the organic active transistor material in each case

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being respectively a p-channel organic semiconductor material or an n-channel organic semiconductor material, that separate gate electrodes are provided for each of the transistors, that the organic active semiconductor in an organic p-channel transistor in each case is provided electrically isolated from the inorganic n-channel transistor, and that the organic active semiconductor in an organic n-channel transistor optionally is provided electrically isolated from the inorganic p-channel transistor.

According to the invention the inorganic active semiconductor material is advantageously selected among hydrogenated amorphous silicon (a-Si:H),

- hydrogenated or unhydrogenated microcrystalline silicon (µc-Si:H;µc-Si), hydrogenated or unhydrogenated polycrystalline silicon (pc-Si:H;pc-Si), single crystal silicon. copper-doped polycrystalline germanium (pc-Ge:Cu), cadmium selenide (CdSe), cadmium telluride (CdTe), or composite inorganic semiconductors based on said materials. possibly in single crystal form.
 - Where the inorganic thin-film transistor is an n-channel transistor, the inorganic active semiconductor material is preferably amorphous silicon (a-Si:H), and where the inorganic transistor is a p-channel transistor, the inorganic active semiconductor material is preferably a p-channel silicon material, particularly p-channel hydrogenated amorphous silicon (a-Si:H).
- In an advantageous embodiment the active semiconductor material in the inorganic thin-film transistor comprises at least one polyconjugated organic compound with a specific molecular weight. It is then advantageous that the polyconjugated organic compound or compounds are selected selected among conjugated oligomers, polycyclic aromatic hydrocarbons, particularly
 - 25 polyacenes. or polyenes.

Where the organic thin-film transistor is a p-channel transistor, it is advantageous that the organic active semiconductor material is pentacene, and where the organic thin-film transistor is an n-channel transistor, it is advantageous that the organic active semiconductor material is copper

30 hexadecafluorophtalocyanide.

Finally, it is according to the invention particularly advantageous that the source electrode and the drain electrode of the organic thin-film transistor is provided in one and the same level in the thin-film structure of the organic thin-film transistor.

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isolated from the inorganic n-channel transistor and optionally providing the organic thin-film transistor on the same level in the thin-film structure of the p-channel organic active semiconductor material or correspondingly forming A first method for fabricating an integrated inorganic/organic complementary n-channel organic active semiconductor material and a p-channel inorganic the organic thin-film transistor as an n-channel transistor and the inorganic forming the inorganic thin-film transistor as an n-channel transistor and the thin-film transistor as a p-channel transistor by depositing respectively an organic active semiconductive material in an organic n-channel transistor depositing material for the source electrode and the drain electrode of the organic thin-film transistor and in each case providing the organic active respectively an n-channel inorganic active semiconductor material and a thin film transistor circuit is according to the invention characterized by semiconductor material in an organic p-channel transistor electrically active semiconductor material, depositing separate gate electrodes for respectively the first and the second transistor on a common substrate, organic thin-film transistor as a p-channel transistor by depositing electrically isolated from the inorganic p-channel transistor.

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electrodes of the first transistor in form of a second metal over the source and the whole organic thin-film transistor and patterning this such that the source hydrogenated polycrystalline silicon (n*pc-Si:H) as source and drain contacts characterized by comprising steps for depositing separate gate electrodes of a layer level in the thin-film structure, forming an isolating double layer over electrodes for the second transistor in the form of a third metal in the same gate electrode, depositing an inorganic active semiconductor in the form of and drain electrodes and the gate isolator in the second transistor become exposed, whereafter a layer of pentacene is deposited above the isolating hydrogenated amorphous silicon (a-Si:H) above one of the gate electrodes which thus forms the gate electrode of the first transistor, depositing and depositing separate inorganic isolators of silicon nitride (SiN $_{\!\scriptscriptstyle X})$ over each complementary thin-film transistor circuit is according to the invention patterning an \boldsymbol{n}^{\star} doped layer of either hydrogenated amorphous silicon drain contacts thereof, depositing and patterning the source and drain for the first transistor, depositing and patterning the source and drain $(\pi^{+}a\text{-}Si\text{:}H)$ or hydrogenated microcrystalline silicon (n $^{+}\mu\text{c--}Si\text{:}H)$ or first metal for each of the two transistors on a common substrate, A second method for fabricating an integrated inorganic/organic 35 8

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layer in the exposed portion forming the active semiconductor material of the double layer and the exposed portion of the second transistor, the pentacene the additional pentacene layer broken by a re-entrant edge of the profile of organic thin-film transistor and being provided electrically isolated against the isolating double layer.

realized in a tri-layer process which forms an inverted staggered three-layer In an advantageous embodiment of the last-mentioned method according to the invention the steps for forming the inorganic thin-film transistor are structure.

In another advantageous embodiment of the last-mentioned method according to the invention the steps for forming the inorganic thin-film transistor are realized in a back-channel etch process. 으

In an advantageous embodiment of the last-mentioned method according to double layer of polymethylmetacrylate (PMMA) and Novolac photoresist. organic thin-film transistor is isolated by a re-entrant profile of a broken the invention the active semiconductor in the form of pentacene in the

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In an advantageous embodiment of the last-mentioned method according to the invention gold is evaporated thermally for forming the source and drain electrodes of the organic thin-film transistor.

Finally, the pentacene layer which is deposited over the isolating double layer can optionally be removed. ಣ

exemplary embodiments and with reference to the accompanying drawings The invention shall now be explained in more detail in connection with

fig. I shows a complementary thin-film transistor circuit according to prior art as exemplified by the above-mentioned US patent No. 5 675 199,

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fig. 2a a first embodiment of the complementary thin-film transistor circuit according to the invention,

fig. 2b a second embodiment of a complementary thin-film transistor circuit according to the invention,

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fig. 2c a variant of the embodiment in fig. 2b,

PCT/NO99/00208 WO 99/66540 fig. 3a a third embodiment of the complementary thin-film transistor circuit according to the invention.

fig. 3b a fourth embodiment of the complementary thin-film transistor circuit according to the invention.

fig. 3c a fifth embodiment of the complementary thin-film transistor circuit according to the invention.

fig. 3d a variant of the embodiment in fig. fig. 3c,

figs. 4a-4r schematically the process steps in an embodiment of a method according to the present invention,

figs. 5a-5d a tri-layer etch process as used with a method according to the present invention. 2

figs. 6a-6c a back-channel etch process as used with a method according to the present invention.

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complementary thin-film transistor circuit according to the present invention, fig. 7a schematically a section through an inverter realized with the 15

fig. 7b the circuit diagram of the inverter in fig. 7a.

fig. 7c a line drawing based on a microphotograph of the actual inverter in fig. 7a realized in thin film technology.

fig. 8a the voltage transfer curve for an inverter realized as in fig. $7\mathrm{a}_{\mathrm{i}}$

fig. 8b a diagram of the transient current for an inverter realized as in fig. 7a, fig. 9a a line drawing based on a microphotograph of an actual NAND gate realized with complementary thin-film transistor circuits according to the present invention,

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fig. 9b a circuit diagram of the NAND gate in fig. 9a,

fig. 9c the output voltage of the NAND gate in fig. 9a, 22

fig. 10 a line drawing based on a microphotograph of an actual five-stage ring oscillator realized with complementary thin-film transistor circuits according to the present invention,

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fig. 11 the circuit diagram of the ring oscillator in fig. 10.

figs. 12a-12c respectively the gate delay, the power dissipation and the power dissipation product for the ring oscillator in fig. 10 as function of the supply voltage, and

dissipation product as function of the supply voltage for an eleven-stage ring oscillator realized with complementary thin-film transistor circuits according figs. 13a-c respectively the gate delay, the power dissipation and the power to the present invention.

rendered in fig. 1. For both transistors a common gate electrode 2 of metal is point. Therein is disclosed a complementary circuit with inorganic n-channel provided on a substrate 1. Over the gate electrode is provided a dielectric 3 thin-film transistor and an organic p-channel thin-film transistor, such as above-mentioned US patent No. 5 625 199 (Baumbach & al.) as starting First there shall now be given a discussion of prior art with the 2

isolating material, for instance silicon nitride, polyimide or another dielectric of n° amorphous silicon has been deposited and provides electrical contact to The contact metal may be made of an evaporated or sputtered layer of Au or prior art circuit comprises the drain electrode 10 of the p-channel transistor. transistor and forms the source contact therein. Now follows a layer 8 of an areas of the n-channel transistor. Over the layers 3, 4 and 5 a further layer 6 deposited patterned such that the source electrode and drain electrode of the patterned such that the n-channel and the p-channel transistors in the circuit in order to isolate the source/drain electrodes 7 against the active organic which for instance may be deposited by vacuum sublimation. Finally, the non-conducting polymer. Over the gate isolator 3 then follows a layer 4 of layer 5 which serves to prevent short circuit between the source and drain undoped amorphous silicon which forms the active layer of the inorganic n-channel transistor. On the a-Si layer 4 is provided a patterned isolation n-channel transistor are not short-circuited. The metal layer 7 is besides semiconductor layer 9 which is formed of $\alpha\text{-hexathienylene}\left(\alpha\text{-}6T\right)$ and Ag and will be connected to the positive supply voltage. This prior art the active amorphous silicon layer 4. The source/drain electrodes 7 are are connected. Consequently the layer 7 extends towards the p-channel complementary transistor circuit is then in a final step coated with a which forms the gate isolator and which typically is made of a 2 25 ಣ

circuit.

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electrode of organic transistor. The broken re-entrant profile and the isolating transistor is exposed, the isolating double layer in this area in section having provided in the form of a layer over the isolating double layer where this has semiconductor material contacts both the source and the drain electrodes of deposited on a substrate and covered by a layer of silicon nitride which forms extends beyond this where it forms n* doped areas for source and drain in the material of the source electrode of the inorganic transistor may be of another such that the portion between the source and drain electrodes in the organic the gate isolator. The inorganic active semiconductor material is here shown electrode is itself then deposited over the active semiconductor material and deposited over the gate isolator such that the source and drain electrodes of polymethylmetacrylate and Novolac photoresist is provided, but patterned in the form of hydrogenated amorphous silicon (a-Si:H) and provided such A section through a first embodiment of a complementary transistor circuit that it registers with the gate electrode of the inorganic transistor, but also inorganic transistor. The contact material proper for the drain or source thin-film structure. Over both the inorganic and the organic transistors' metal than the metal in the gate electrode. Correspondingly the contact material for the source and drain electrodes of the organic transistor is a re-entrant profile. The organic active semiconductor material is now the organic transistor in each case are located on the same level in the the organic transistor and simultaneously also registers with the gate mutually isolated by a patterned isolation layer of silicon nitride. The electrodes for respectively the inorganic and the organic transistor are not been removed and in the exposed portion thereof, such that the according to the present invention is shown in fig. 2a. Separate gate source and drain contacts a double layer of respectively 23 ຊ 2 2

It is to be understood that the active inorganic semiconductor material is not restricted to a hydrogenated amorphous silicon, but may well consist of 35

semiconductor material optionally may be removed where it covers the

solating double layer. In fig. 2a it is, however, retained.

double layer provide a secure electrical isolation between the organic

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transistor and the inorganic transistor. Of course, the active organic

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comprehensive discussion of these materials it shall besides be referred to the polyconjugated organic compounds with suitable properties and be formed by ortho-fused or ortho- and peri-fused aromatic polycyclic hydrocarbons with 4 and T_2 independently represent –H or a lower alkyl and ${f r}$ is an integer which several such. As example of such polyconjugated organic compounds and as have a molecular weight which is not greater than about 2000. For a more to 20 fused rings, polyenes with the formula H-C(T₁)=C(T₂)– H where T₁ Correspondingly the organic active semiconductor material in the organic which includes or consists of phenylene groups which may be substituted, may vary from 8 to 50, as well as conjugated oligomers whose repeating known in the art, it may be mentioned conjugated oligomers, the units of organic semiconductor transistor contain at least 8 conjugated bonds and drain material may also be deposited separately and be different from the hydrogenated microcrystalline or polycrystalline silicon. The source and polyconjugated compound used as active semiconductor material in the transistor is not restricted to pentacene, but may generally be made of channel area, e.g. n* doped microcrystalline hydrogenated silicon. units contain at least a five-link heterocycle. Generally shall a above-mentioned US patent no. 5 347 144 (Garnier & al.). 2 2

material by etching, as such materials usually are damaged or destroyed when they are subjected to common photoresists and chemicals for treatment of the simplified version of the complementary thin-film transistor circuit. In fig. 2b removed such this is shown in fig. 2c. In each case the active semiconductor inorganic transistor. In that connection it shall be remarked that generally it photoresist. However, it has turned out that a water-based etch process with material is removed outside the organic thin-film transistor. The mask layer material in the organic transistor becomes electrically isolated against the semiconductor material in the p-channel transistor may be achieved with a water-based material provides very good results. In the patterning of e.g. of the photoresist may be retained as shown in fig. 2b, but it may also be organic optoelectronic material may e.g polyvinyl alcohol as solvent and As an alternative to the embodiment in fig. 2a. the isolation of the active has been regarded as a problem to remove active organic semiconductor gelatine as photoresist be an advantageous alternative. Besides are both thin-film transistor circuit, whereafter the organic active semiconductor this is shown by providing a photoresist layer over the complementary 8 35 23 2

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photolithography and printing other possible alternatives to etching – particularly printing may in the long run turn out to be both the simplest and cheapest.

Fig. 3a shows a section through an organic/inorganic thin-film transistor according to the present invention where an organic thin-film transistor with an n-channel organic semiconductor is employed. Fig. 3 shows the simplest embodiment possible, wherein separate gate electrodes are provided on the substrate, the gate isolator consists of the same material in both cases and the metal for the source/drain electrode similarly is the same for both transistors.

As an example of an organic n-channel material may be mentioned copper hexadecafluorophtalocyanine (F₁₆CuPc) (see Y.Y. Lin & al... Organic complementary ringoscillators"; Appl. Phys. Lett., Vol. 74 No. 18 (1999)). This organic semiconductor shows field-effect mobilities up to 10⁻² cm/Vs and is not as sensitive to external conditions as other organic semiconductor.

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15 materials of the n-type such as buckminsterfullerene (C₆₀).

Organic n-channel thin-film transistors based on copper-hexadecafluorophialocyanine (Fi6CuPc) or another organic semiconductor material of the n-type may be combined with one of several inorganic p-channel semiconductor materials in order to form the complementary thin-film transistor circuit.

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As examples of suitable inorganic semiconductors of the p-type may be mentioned p-channel amorphous silicon which has field effect mobilities comparable with F_{In}CuPc. or copper-doped polycrystalline germanium (pc-Ge:Cu) which in the literature is shown used in combination with indium-doped cadmium selenide (Cd-Se:In) in a complementary polycrystalline thin-film technology (see J. Doutreloigne & al., "The electrical performance of a complementary CdSe:In/Ge:Cu thin film

transistor technology for flat panel displays", Solid-State Electronics, Vol. 34 No. 2 (1991)). Polycrystalline germanium has displayed field-effect mobilities of about 5-15 cm²/Vs, but requires a more complicated processing than amorphous silicon.

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Fig. 3b shows an embodiment of the complementary thin-film transistor circuit according to the invention with an n-channel transistor. The embodiment in fig. 3b is analog to that in fig. 2a, but with the same metal used for the source and drain electrodes in both transistors. The isolating double layer may be realized as in fig. 2a. namely consisting of polymethylmetacrylate and Novolac photoresist such that the portion above the n-channel organic semiconductor is exposed, the isolating double layer also here being broken by a re-entrant profile. The active semiconductor in the n-channel organic transistor will then be isolated from the p-channel inorganic transistor, something which may be advantageous, but which is not a necessary condition for using an organic active n-channel semiconductor

The isolation of the organic active n-channel semiconductor material may also be achieved in corresponding manner as shown for the embodiment in fig. 2b, namely as shown in fig. 3c, where a photoresist is etched and masked such that the n-channel organic active semiconductor is isolated. The etch mask. i.e. the photoresist, may also here be removed from the organic n-channel transistor and it is then obtained the variant which is shown in fig 3d of the embodiment in fig. 3c.

echnology be given a description of specific features in the fabrication of the consisting of polymethylmetacrylate (PMMA) and Novolac photoresist which thin-film transistor were deposited by means of thermal evaporation. In order inorganic thin-film transistor. The source and drain electrodes of the organic inorganic a-Si:H thin-film transistor is made in a process which provides an inverted staggered three-layer structure, something which shall be described There shall now with reference to figs. 4a-4r which schematically show the techniques as well as sputtered deposition of source and drain metal for the transistor, in this case pentacene, a re-entrant photoresist profile was used complementary thin-film transistor circuit according to the invention. The circuit. This is a necessary step, as thin-film transistors with pentacene as together forms an isolating double layer in the complementary transistor more closely in the following. The layers of a-Si:H/SiN were deposited process scheme for integrated complementary a-Si:H organic transistor using of plasma-enhanced chemical vapour deposition. The subsequent process step comprises standard lithographic methods and wet etching to isolate the active semiconductor material of the organic thin-film 35 ន 25 30

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leakage in the pentacene layer, but as pentacene is sensitive to most forms of With the method according to the invention the isolation is achieved during threshold, i.e. a positive voltage must be used on the gate electrode to turn photolitography after the deposition of the organic semiconductive layer. the deposition of the pentacene layer by breaking this over the re-entrant double-layer profile in the organic transistor. The maximum temperature semiconductor of pentacene in the organic transistor in order to prevent chemical processing, it is difficult to achieve isolation with the use of p-channel active semiconductor material usually will have a positive the transistor off. It is hence necessary to isolate an active p-channel which was used during the fabrication was 250°C.

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uppermost silicon nitride layer is etched and in the subsequent process step in the lowermost nitride layer by means of a third mask III. The etching itself of photoresist is now patterned with another mask II in order to actively define a fig. 4f the layer of hydrogenated amorphous silicon is etched. In the process In fig. 4a the gate electrode metal is deposited on the substrate by sputtering shown in fig. 4b. By means of plasma-enhanced chemical vapour deposition, a tri-layer structure is thereafter deposited. consisting of a gate isolator $\mathrm{SiN}_{\mathbf{x}}$ step shown in fig. 4g a photoresist is patterned for etching of i-stopper and however, substantially will be self-explanatory to a person skilled in the art. explicitly be discussed with a concrete short reference to figs. 4a-4r which, silicon and finally an isolation layer, once again formed of silicon nitride, over both gate electrodes. thereabove a layer of hydrogenated amorphous Now the process steps for the fabrication of a transistor of this kind shall and then the separate gate electrodes are patterned with a first mask I as thin-film transistor with hydrogenated amorphous silicon. In fig. 4e the such as shown in fig. 4c. In the subsequent step shown in fig. 4d a 25 13 2

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from the first metal used in the gate electrodes. In the process step shown in fig. 41 the source/drain metal M2 for the organic transistor was lifted off and chemical vapour deposition and in the subsequent process step in fig. 4j this lift-off of source/drain electrode metal. This is sputtered in the process step as shown in fig. 4k and is denoted with M2 which may be a metal different In order to realize the source and drain areas of the n-channel transistor as shown in fig. 41 n⁺ a-Si:H is now deposited by means of plasma-enhanced takes place by means of a fourth mask IV for patterning a photoresist for

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the i-stopper and the lowermost silicon nitride layer is shown in fig. 4h.

then follows in the process step shown in fig. 4m an etching of the n layer of hydrogenated amorphous silicon which hence shall provide the source and drain areas of the inorganic transistor.

ig. 4q. Finally is now the organic active semiconductor material deposited in Now follows in the process step shown in fig. 4n a patterning of a photoresist re-entrant broken profiles of the isolating double layer, such this is shown in portion the active p-channel semiconductor material of the organic transistor. transistor appears with source and drain electrodes of the metal M3 provided for lift-off of the metallization of the organic thin-film transistor. This takes isolating double layer is patterned such that the source and drain electrodes place by means of a fifth mask V. A metal layer of a third metal M3 is now now by means of photo-lithography deposited a double layer consisting of thin-film transistor electrically against the inorganic thin-film transistor is the form of pentacene over the whole circuit and provides in the exposed follows the lift-off of this metal layer M3, such that the organic thin-film polymethylmetacrylate PMMA and for instance Novolac photoresist. The in the same level in the thin-film structure. In order to isolate the organic of the metal M3 for the organic thin-film transistor are exposed between deposited over the whole transistor circuit, as shown in fig. 40, and then 2 2

complementary organic thin-film transistor circuit according to the invention It shall be understood that the pentacene layer where it covers the isolating double layer besides may be removed therefrom in a concluding not shown process step. Further may, of course, electrically isolating passivation and planarization layers be deposited over the whole complementary thin-film circuit, such this is known in the art. but not here specifically shown. The now appears substantially as shown in fig. 4r and corresponding to the embodiment shown in fig. 2a.

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deposited on the patterned gate electrode. The uppermost silicon nitride layer the source and drain electrodes is patterned and the doped amorphous silicon The tri-layer etch process as used with the present invention and as rendered hydrogenated silicon is deposited all over as shown in fig. 5c. The metal of somewhat greater detail with reference to figs. 5a-5d. In the tri-layer etch hydrogenated amorphous silicon and a further layer of silicon nitride are in the process steps as shown in figs. 4c-h shall now be discussed in process as shown in fig. 5a, a triple layer of silicon nitride, undoped is patterned as shown in fig. 5b and an n* doped layer of amorphous 35

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material over the uppermost silicon nitride layer etched away, as shown in fig. 5d. As the uppermost silicon nitride layer protects the channel area in the inorganic thin-film transistor, this etch step is not critical. However, the tri-layer process requires two deposition steps of amorphous silicon and as the source and drain electrodes must be patterned on the top of the uppermost silicon nitride layer which is patterned with the channel length, this requires a more aggressive photolithography for a given channel length.

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The back-channel etch process is shown in fig. 6a-6c. An isolation layer of silicon nitride is deposited over the gate electrode and the substrate, and followed by undoped hydrogenated silicon and n⁺ doped silicon as well as a further layer of n⁺ doped hydrogenated amorphous silicon. This is shown in fig. 6a. The source and drain electrodes are patterned and the doped hydrogenated amorphous silicon in the channel area is etched away, such this is shown in fig. 6b and fig. 6c respectively. The back-channel etch process is very simple, but the etching of the n⁺ doped hydrogenated amorphous silicon in the channel area is a critical step. Typically back-channel etching results in incorganic thin-film transistors with poorer quality than that may be obtained by using a three-layer etch process.

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invention. Functionally the inverter in fig. 7a corresponds substantially to the electrode contact may then be deposited in the same process step as shown in transistor as well as the inverter gate contact against the inorganic transistor. nverter is based on a p-channel semiconductor material, viz. pentacene, and but is based on the embodiment according to the present invention such this semiconductor material in the inorganic transistor. As the input signal to the complementary transistor circuit according to prior art as rendered in fig. 1, fig. 4a-4b with the use of mask I. As in fig. 2a the isolating double layer of polymethylmetacrylate on Novolac photoresist will isolate both the organic nydrogenated amorphous silicon in doped and undoped form is used as the nverter shall be conveyed to the gate electrodes, there is for this purpose for instance is shown in fig. 2a. As therein the organic transistor of the nverter. be removed. The well-known schematic circuit diagram of the Fig. 7a shows a schematic section through an inverter formed with the provided a gate electrode contact as shown to left in fig. 7a. This gate Besides may also here the pentacene layer which is provided over the solating double layer as well as over the gate electrode contact of the integrated complementary thin-film transistor circuit according to the 22 3 33 2

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inverter shown in fig. 7b and an inverter realized with use of a complementary transistor circuit and a method according to the invention is shown by the line drawing in fig. 7c. The organic thin-film transistor is here located at left and the inorganic thin-film transistor in the complementary thin-film transistor circuit at right in fig. 7c.

Fig. 8a shows the voltage transfer curves for different supply voltages for an inverter with a β ratio of 1. The β ratio is here defined by

$$\beta = \frac{(W/L)_{u-S:H}}{W/L_{performen}}$$

In this regard it shall be remarked that in CMOS circuits both transistors may be operated both as driver and load. Due to a topological similarity β is sometimes defined as the width/length relationship W/L for the n-channel device divided by the length/width relationship for the p-channel device.

- The inverter shows sharp transitions with a gain which exceeds 22 for a supply voltage of 20 V. The on voltage of the inverter is equal to the supply voltage and the off voltage is 0 V. This shows the complete maintenance of the voltage levels of the complementary thin-film transistor circuit according to the invention. The transition current for the inverter reaches a top near the logic transition voltage and is otherwise very low, such this is evident from fig. 8b. This shows that the complementary thin-film transistor circuit

according to the present invention has a true complementary behaviour.

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With the complementary thin-film transistor circuit according to the present invention it is, of course, possible to realize logic gates as otherwise well-known in the CMOS-technology. An example of a complementary NAND-gate realized by means of a complementary transistor circuit according to the present invention is shown in the line drawing in fig. 9a and the corresponding schematic circuit diagram in fig. 9b. By connecting the output of the NAND gate to the inverter shown in fig. 7c a complementary AND gate is of course obtained, the output of which then becoming the inverted of the output signal from the NAND gate. The voltage transfer curve for different input voltages for the NAND gate is shown in fig. 9c and has the same properties as the voltage transfer curves for these are shown in fig. 8a. A person skilled in the art will, of course, realize that generally may all logic gates as known in the CMOS technology and the

corresponding Boolean functions be realized with the use of a NAND gate as

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complementary thin-film transistor circuit according to the invention is generally used for realizing logic gates in complementary thin-film shown in fig. 9a and inverters as shown in fig. 7c. The integrated technology By means of the integrated complementary thin-film circuits ring oscillators ratios. These ring oscillators show a single gate delay as low as 5 µs, a gate power dissipation less than 0.2 µW per stage and a power delay product as were made with respectively 5 and 11 inverter stages and with different $\boldsymbol{\beta}$ voltage, such that high operating frequencies may be obtained with the low as 15 pJ. The gate delay decreases fast with the increasing supply relatively low supply voltage. 2

A line drawing of a five-stage ring oscillator is shown in fig. 10 and with the circuit diagram rendered in fig. 11. In addition to the five inverter stages an shown five-stage ring oscillator, fig. 12b power dissipation and fig. 12c the power delay product for the same, all figures showing these characteristics inverter stage can be derived. Fig. 12a shows the single gate delay for the additional sixth inverter is used for isolating the circuit from the capacity oad of an oscilloscope used for measuring the characteristics of the ring oscillator. From the measured oscillation frequency the delay of a single for a β ratio of 1/2.

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according to the present invention, but not shown herein. Fig. 13a, 13b and 13c, however, show the corresponding characteristics for this eleven-stage A ring oscillator with eleven inverter steps is realized in corresponding manner with the use of the integrated complementary thin-film circuit ring oscillator as shown in fig. 12a-12c, but with a β ratio of 1/3.

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The methods according to the present invention are simple and hence make it amplification and very good maintenance of the logic level in addition to low so-called "lap-tops" or for low-level implementation such as programmable possible to fabricate integrated complementary thin-film transistor circuits according to the invention at low costs. Complementary transistor circuits have an inherent low static power consumption, something which is of applicable in control circuits for liquid crystal displays in portable PCs, complementary thin-film transistor circuit according to the invention importance for applications based on battery power. This makes the tags. The circuits according to the invention have high switching

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static power consumption. The gate delay in the transistor circuits fabricated mentioned as low as 5µs, the fastest speed up to now obtained with circuits according to the invention measured by means of ring oscillators is as which use organic transistors.

- transistor a p-channel transistor or vice versa, is of course, not restricted to inorganic semiconductor materials makes it probable that in the future both organic thin-film transistor may be an n-channel transistor and the organic materials with further improved properties may be employed. Composite use of the active semiconductor materials as mentioned in the exemplary The hybrid integrated complementary thin-film technology, wherein the embodiments. The on-going development of suitable organic as well as correspondingly n- as well as p-channel inorganic active semiconductor n- as well as p-channel active organic semiconductor materials and 2 2
- to single crystal silicon, while on the other hand gallium arsenide for the time being appears less probable, but shall in no way be excluded in future hybrid inorganic semiconductor compounds may be of interest and the same applies complementary thin-film transistor circuits of the kind disclosed herein.

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CLAIMS

- connected and provided on a common substrate, wherein the first transistor is organic active transistor material in each case being respectively a p-channel An integrated inorganic/organic complementary thin-film transistor thin-film transistor, and wherein the complementary thin-film transistor the inorganic thin-film transistor is an n-channel transistor and that the circuit comprising a first and a second transistor which are operatively organic thin-film transistor is a p-channel transistor, or vice versa, the an inorganic thin-film transistor and the second transistor an organic circuit forms a multilayer thin-film structure, characterized in that
 - that the organic active semiconductor in an organic p-channel transistor in organic semiconductor material or an n-channel organic semiconductor that separate gate electrodes are provided for each of the transistors, 2
 - that the organic active semiconductor in an organic n-channel transistor optionally is provided electrically isolated from the inorganic p-channel each case is provided electrically isolated from the inorganic n-channel transistor, and

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- unhydrogenated polycrystalline silicon (pc-Si:H;pc-Si), single crystal silicon, characterized in that the inorganic active semiconductor material is selected unhydrogenated microcrystalline silicon (µc-Si:H;µc-Si), hydrogenated or A complementary thin-film transistor circuit according to claim 1, among hydrogenated amorphous silicon (a-Si:H), hydrogenated or 2
 - (CdSe), cadmium telluride (CdTe), or composite inorganic semiconductors copper-doped polycrystalline germanium (pc-Ge:Cu), cadmium selenide A complementary thin-film transistor circuit according to claim 2 based on said materials, possibly in single crystal form. 22
 - characterized in that the inorganic active semiconductor material is wherein the inorganic transistor is an n-channel transistor, hydrogenated amorphous silicon (a-Si:H). ဓ
- A complementary thin-film transistor circuit according to claim 2, characterized in that the inorganic active semiconductor material is a wherein the inorganic transistor is a p-channel transistor,

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p-channel silicon material, particularly p-channel hydrogenated amorphous silicon (a-Si:H).

- thin-film transistor comprises at least one polyconjugated organic compound 5. A complementary thin-film transistor circuit according to claim 1, characterized in that the active semiconductor material in the organic with a specific molecular weight.
- characterized in that the polyconjugated organic compound or compounds are A complementary thin-film transistor circuit according to claim 5, selected among conjugated oligomers, polycyclic aromatic hydrocarbons,
 - particularly polyacenes, or polyenes. 2
- A complementary thin-film transistor circuit according to claim 6, characterized in that the organic semiconductor material is pentacene. wherein the organic thin-film transistor is a p-channel transistor,
- A complementary thin-film transistor circuit according to claim 1, characterized in that the organic active semiconductor material is copper wherein the organic thin-film transistor is an n-channel transistor, hexadecafluorophtalocyanide (F16CuPc). 15
- A complementary thin-film transistor circuit according to claim 1, organic thin-film transistor are provided in one and the same level in the characterized in that the source electrode and the drain electrode of the thin-film structure of the organic thin-film transistor. 2
- substrate, wherein the first transistor is an inorganic thin-film transistor and characterized by forming the inorganic thin-film transistor as an n-channel complementary thin-film transistor circuit comprising a first and a second transistor which are operatively connected and provided on a common complementary thin-film transistor circuit forms a multilayer thin-film structure with successively deposited and patterned thin-film layers, the second transistor a organic thin-film transistor, and wherein the A method for fabricating an integrated inorganic/organic 10. 25
- depositing respectively an n-channel inorganic active semiconductor material and a p-channel organic active semiconductor material or correspondingly forming the organic thin-film transistor as an n-channel transistor and the transistor and the organic thin-film transistor as a p-channel transistor by norganic thin-film transistor as a p-channel transistor by depositing 8

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substrate, depositing material for the source electrode and the drain electrode of the organic thin-film transistor on the same level in the thin-film structure isolated from the inorganic n-channel transistor and optionally providing the active semiconductor material in an organic p-channel transistor electrically p-channel inorganic active semiconductor material, depositing separate gate electrodes for respectively the first and the second transistor on a common of the organic thin-film transistor and in each case providing the organic organic active semiconductive material in an organic n-channel transistor respectively an n-channel organic active semiconductor material and a electrically isolated from the inorganic p-channel transistor.

first transistor is an inorganic thin-film transistor and the second transistor an circuit forms a multilayer thin-film structure with successively deposited and are operatively connected and provided on a common substrate, wherein the organic thin-film transistor, wherein the complementary thin-film transistor comprising steps for depositing separate gate electrodes of a first metal for thin-film transistor circuit comprising a first and a second transistor which patterned thin-film layers, and wherein the method is characterized by 11. A method for fabricating an inorganic/organic complementary

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- depositing separate inorganic isolators of silicon nitride (SiN $_{x}$) over each each of the two transistors on a common substrate,
 - depositing an inorganic active semiconductor in the form of hydrogenated amorphous silicon (a-Si:H) above one of the gate electrodes which thus gate electrode, 2
- polycrystalline silicon (n*pc-Si.H) as source and drain contacts for the first first transistor in form of a second metal over the source and drain contacts forms the gate electrode of the first transistor, depositing and patterning an transistor, depositing and patterning the source and drain electrodes of the thereof, depositing and patterning the source and drain electrodes for the n⁺ doped layer of either hydrogenated amorphous silicon (n°a-Si:H) or hydrogenated microcrystalline silicon (n*µc-Si:H) or hydrogenated 2 2
 - thin-film structure, forming an isolating double layer over the whole organic whereafter a layer of pentacene is deposited above the isolating double layer and the exposed portion of the second transistor, the pentacene layer in the second transistor in the form of a third metal in the same layer level in the exposed portion forming the active semiconductor material of the organic electrodes and the gate isolator in the second transistor become exposed, thin-film transistor and patterning this such that the source and drain 33

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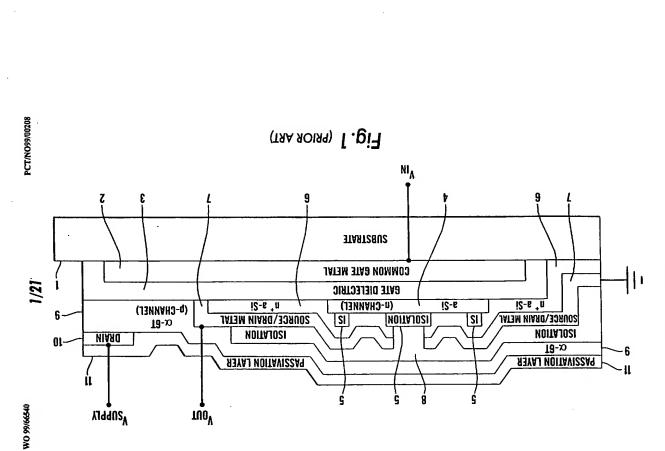
additional pentacene layer broken by a re-entrant edge of the profile of the thin-film transistor and being provided electrically isolated against the isolating double layer.

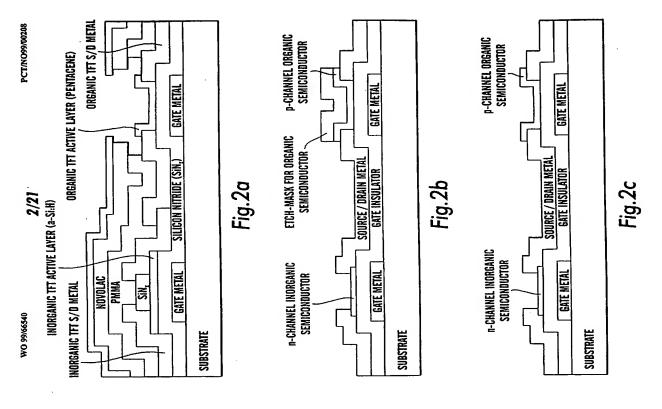
- A method according to claim 11, characterized by realizing the steps for forming the inorganic thin-film transistor in a tri-layer process which forms an inverted staggered tri-layer structure.
- A method according to claim 11, characterized by realizing the steps forming the inorganic thin-film transistor in a back-channel etch process. 13.
- semiconductor in the form of pentacene in the organic thin-film transistor by A method according to claim 11, characterized by isolating the active a re-entrant profile of a broken double layer of polymethylmetacrylate (PMMA) and Novolac photoresist. 2
- thermally for forming the source and drain electrodes of the organic thin-film A method according to claim 11, characterized by evaporating gold transistor.

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A method according to claim 11. characterized by optionally removing the pentacene layer which has been deposited over the isolating double layer. <u>1</u>9.

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SUBSTITUTE SHEET (RULE 26)



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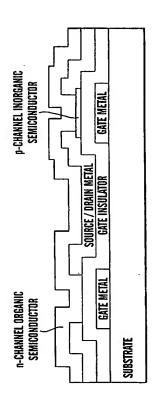


Fig.3a

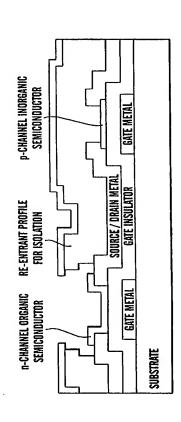
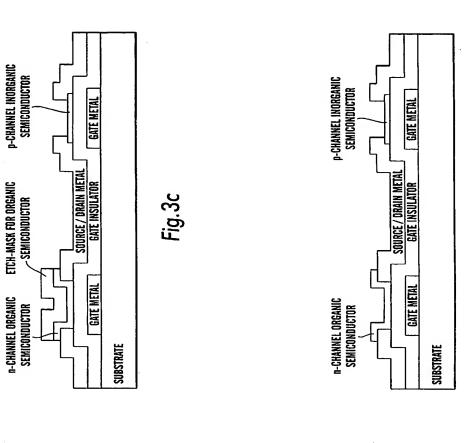


Fig.3b

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Fig.3d



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SPUTTER OF GATE METAL.

GATE METAL Substrate

Fig.4a

DEFINITION OF GATE METAL PATTERN (MASK I):

SUBSTRATE

Fig.4b

PECVD OF TRI-LAYER.

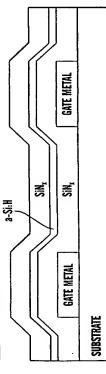


Fig.4c

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PATTERING OF PHOTORESIST FOR ACTIVE DEFINITION OF a-Si:H TFTs (MASK II).

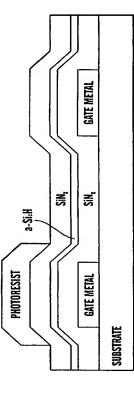


Fig.4d

ETCHING OF TOP NITRIDE LAYER:

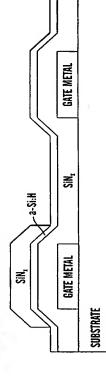


Fig.4e

ETCHING OF a-Si:H LAYER:

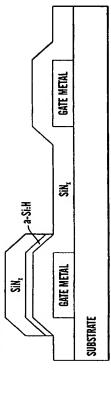


Fig.4f

PATTERNING OF PR FOR ETCH OF 1-STOPPER AND BOTTOM NITRIDE LAYER (MASK III);

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GATE METAL SiN 쯦 n+a-Si:H PATTERNING OF PR FOR LIFTOFF (MASK IV). a-Si:H GATE METAL Sis. S. SUBSTRATE

GATE METAL

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GATE METAL

SUBSTRATE

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H:iS-e~

Fig.4j

ETCHING OF 1-STOPPER AND BOTTOM NITRIDE LAYER:

Fig.4g

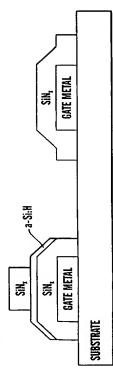


Fig.4h

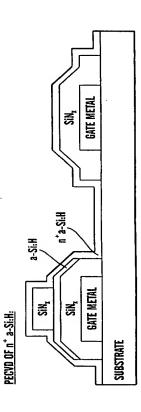
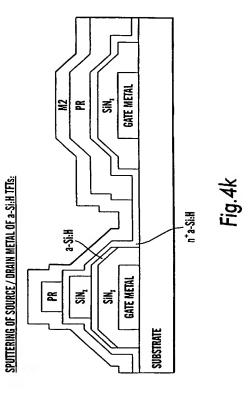
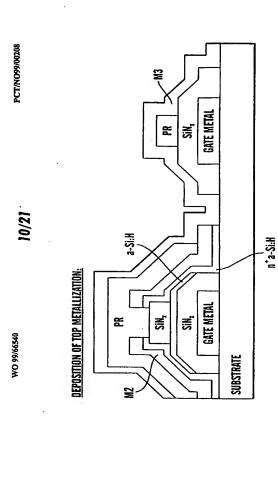


Fig.4i



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GATE METAL

GATE METAL

SUBSTRATE

SiN

Fig.4

ETCHING OF n*LAYER:

N.S.

n⁺a-Si:H

a-Si:H

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LIFTOFF OF a-Si:H SOURCE / DRAIN METAL:

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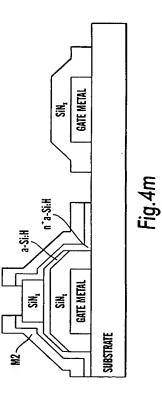
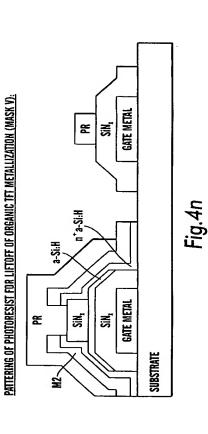


Fig.40



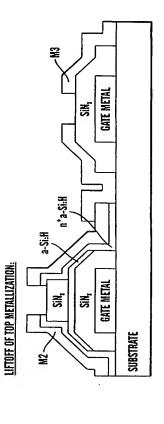
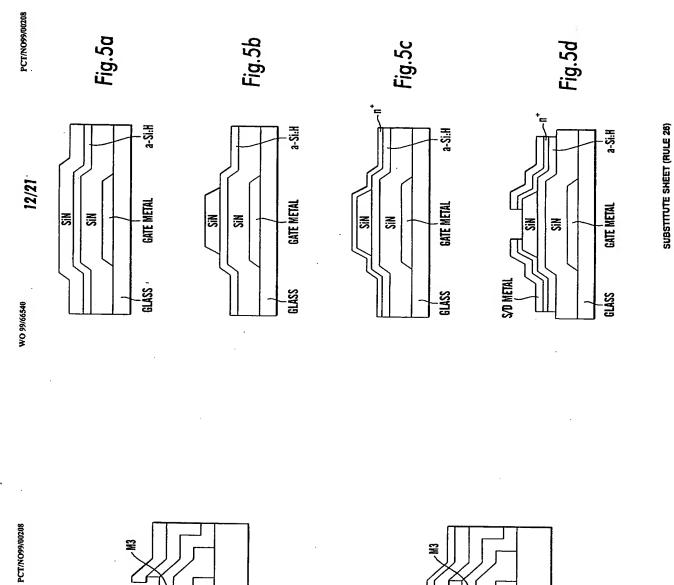


Fig.4p



GATE METAL

GATE METAL

SUBSTRATE

Si.

Fig.4q

n⁺a-Si:H

SiN

품

Sik

a-Si:H

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DOUBLE LAYER LITHOGRAPHY FOR ISOLATION.

PENTACENE

a-Si:H

DEPOSITION OF PENTACENE ORGANIC SEMICONDUCTOR.

GATE METAL

GATE METAL

SUBSTRATE

Sin

S.

SiN

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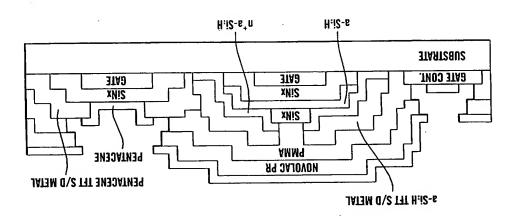
Fig.4r

n⁺a-Si:H

GATE METAL

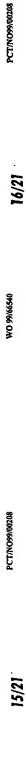
S.

Fig.∑a



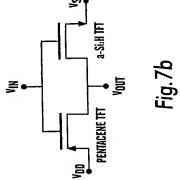
GATE METAL NS:

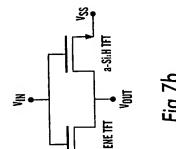
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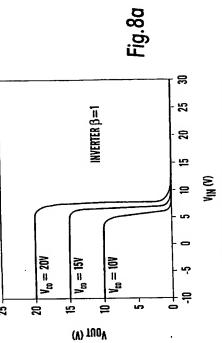


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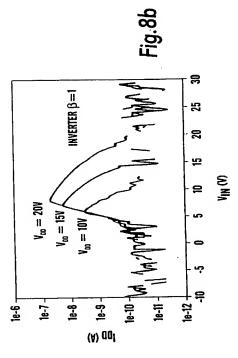


VOLTAGE TRANSFER CURVE OF a-Si.H / PENTAGENE INVERTER

SS

¥

Ve V



TRANSIENT CURRENT OF a-Si:H / PENTACENE INVERTER

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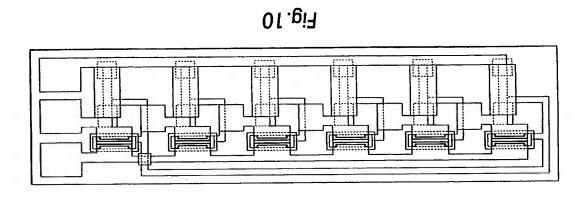
a-Si:H TFT

PENTACENE TFT

Vout

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NAND - VOLTAGE TRANSFER

 $V_{no} = 20V$

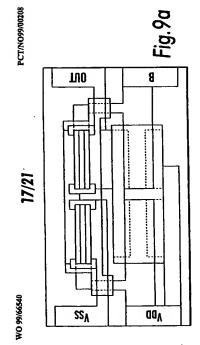
22

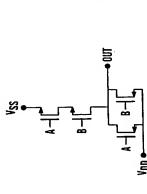
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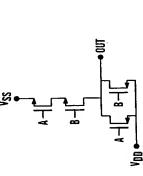
(V) 39ATJOV TU9TUO 전 등

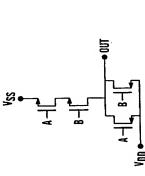


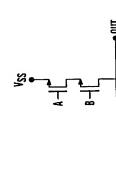
Fig.9c

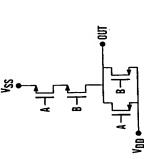


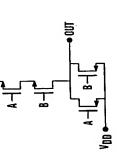


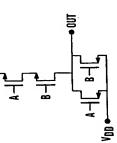




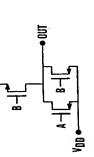


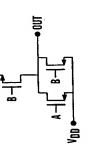


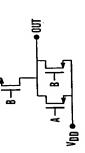






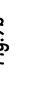








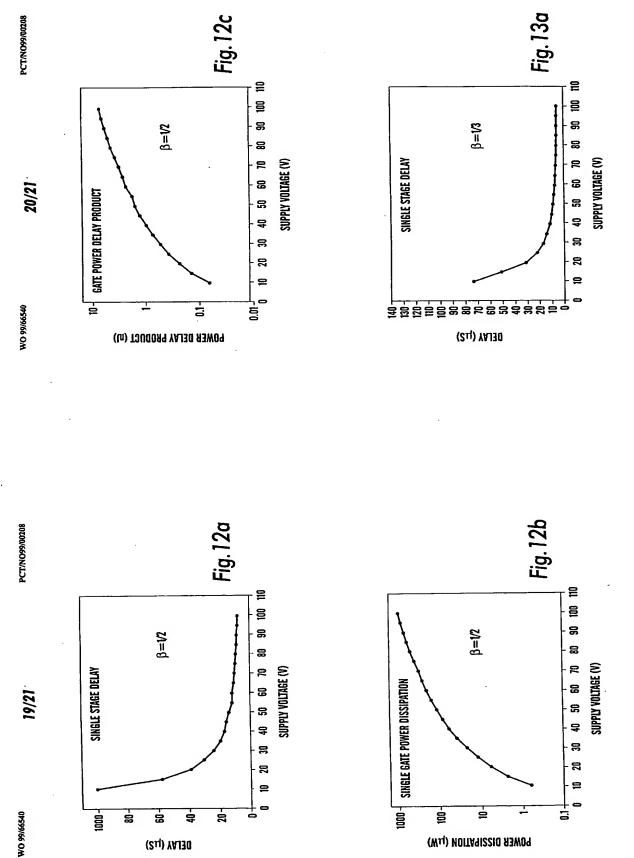








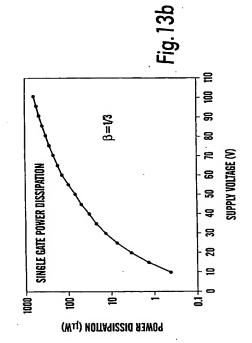


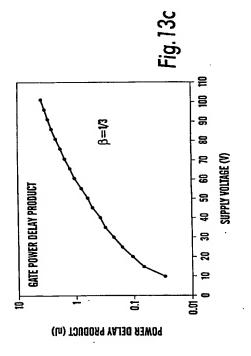


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PCT/NO99/00208





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INTERNATIONAL SEARCH REPORT

International application No. PCT/NO 99/00208

A. CLAS	CLASSIFICATION OF SUBJECT MATTER	
IPC7:	IPC7: H011 29/786, H011, 51/40 Arcarding to International Patent Chastification (UFC) or to both national elastification and UPC	
Minimum of	B. FHELDS SEARCHED Minimum documentation gascehel (classification system followed by classification symbols)	
1007 - 1011	Itom	
Documenta	Documentation rearched other than minimum documentation to the extent that roch documents are included in the fields rearched	the fields scarched
SE, DK, FI, NO	FI,NO classes as above	٠
Electronic	Flectronic data base consulted during the international search (name of data base and, where practicable, search terms used)	l terms used)
C. DOCL	DOCUMENTS CONSIDERED TO BE RELEVANT	
Category	Giation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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>		5-7,11,15
Α		8,12-14,16
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>	EP 0786820 A2 (MOTOROLA, INC.), 30 July 1997 (30.07.97), see the whole document	5-7,11
<		1-4,8-10, 12-16
	1	
I Z	Further documents are listed in the continuation of flox C. X See patent family mues.	
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⋖			1-4,7-14,16
: ~	 US 5625199 A (JOERG BAUMBACH ET AL), 29 April 1997 (29 04 97) see the whole document	766	7,11
⋖			1-6,8-10, 12-16
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International amplication No.	PCT/NO 99/00208
INTERNATIONAL SEARCH REPORT	Information on patent family members 02/11/99

Publication date		05/09/97	11/05/95 21/04/93 10/01/92 23/01/92 17/07/92	23/07/97 31/07/97
Patent family member(s)	NONE	JP 9232589 A	DE 69104204 D,T EP 0537240 A,B FR 266430 A,B WO 9201313 A FR 2671542 A	EP 0785578 A JP 9199732 A
Publication date	18/03/97	30/07/97	13/09/94	29/04/97
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